Spectra of Cosmic Rays escaping from Star Clusters

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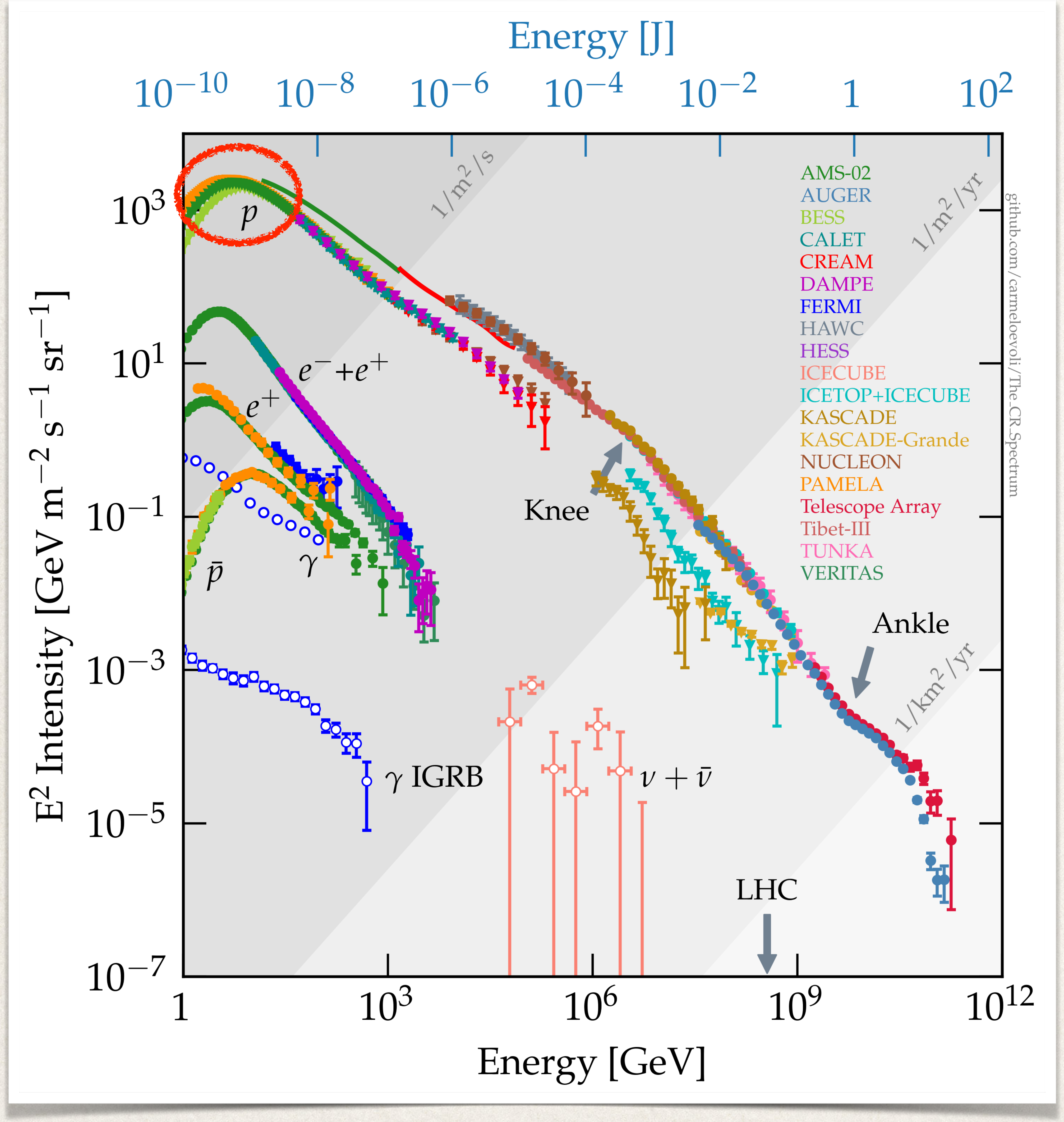
How to explain the origin of Galactic CRs



Requirements

- **Luminosity:** $\sim 10^{40}$ erg/s

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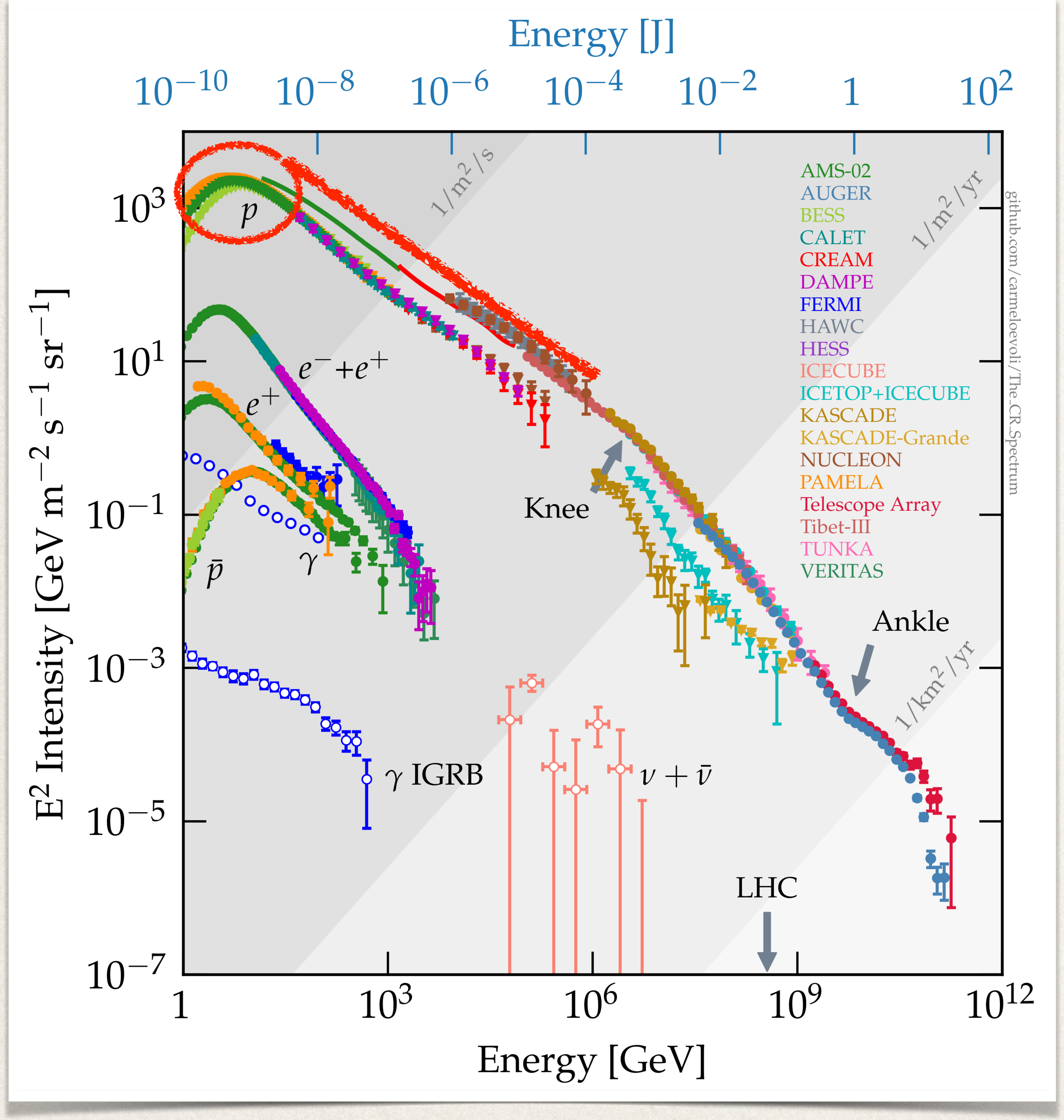

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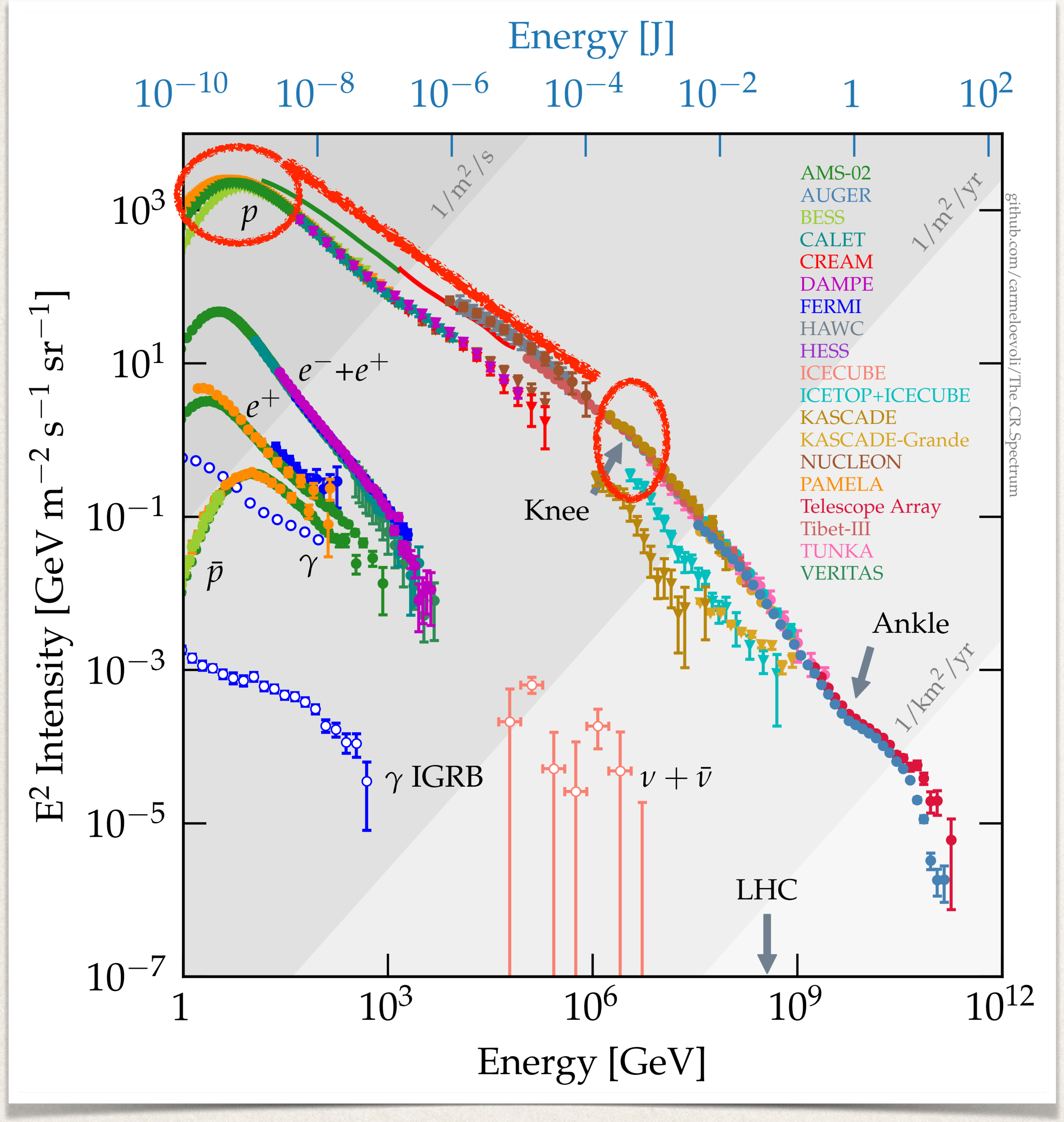

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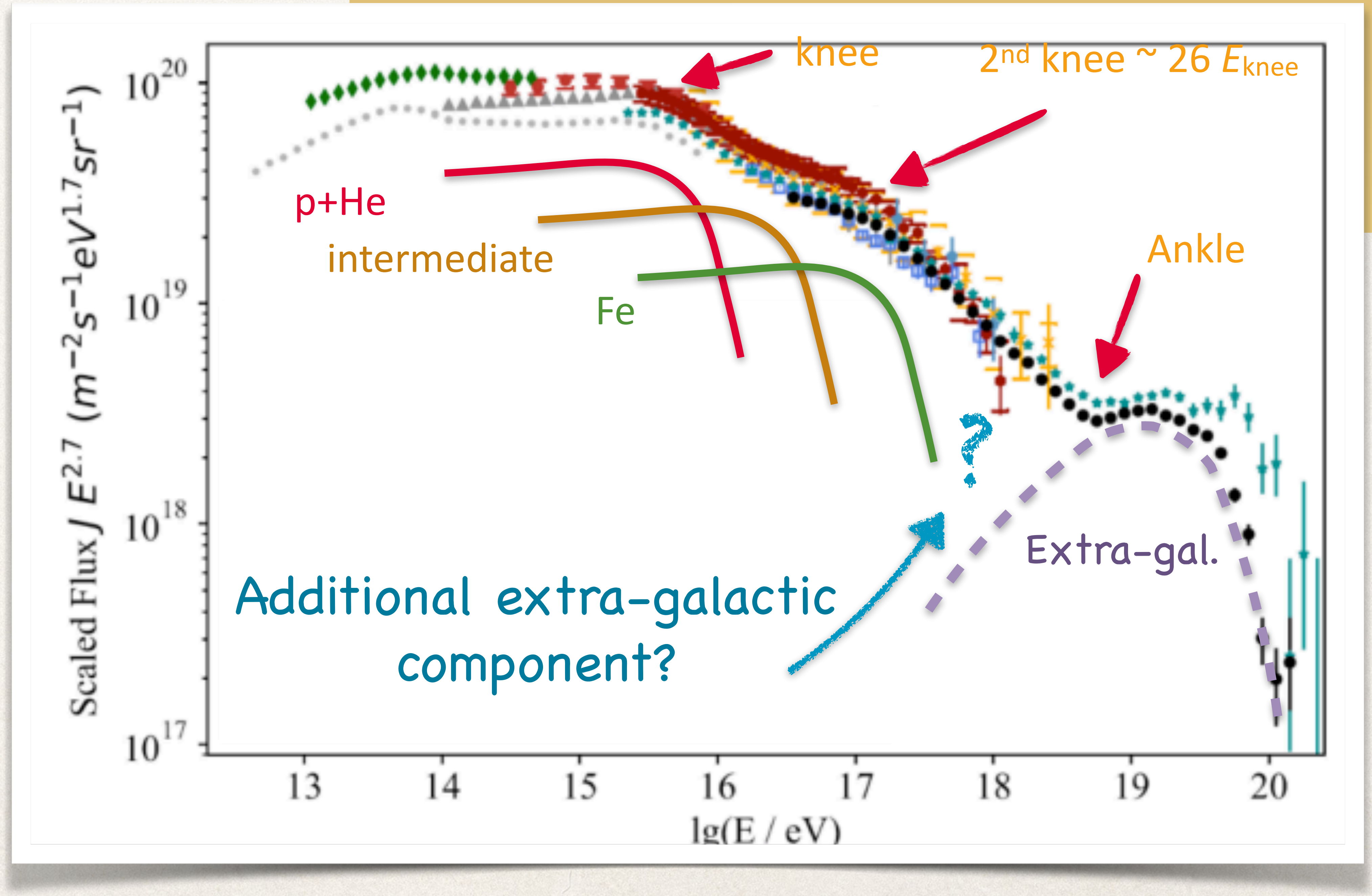

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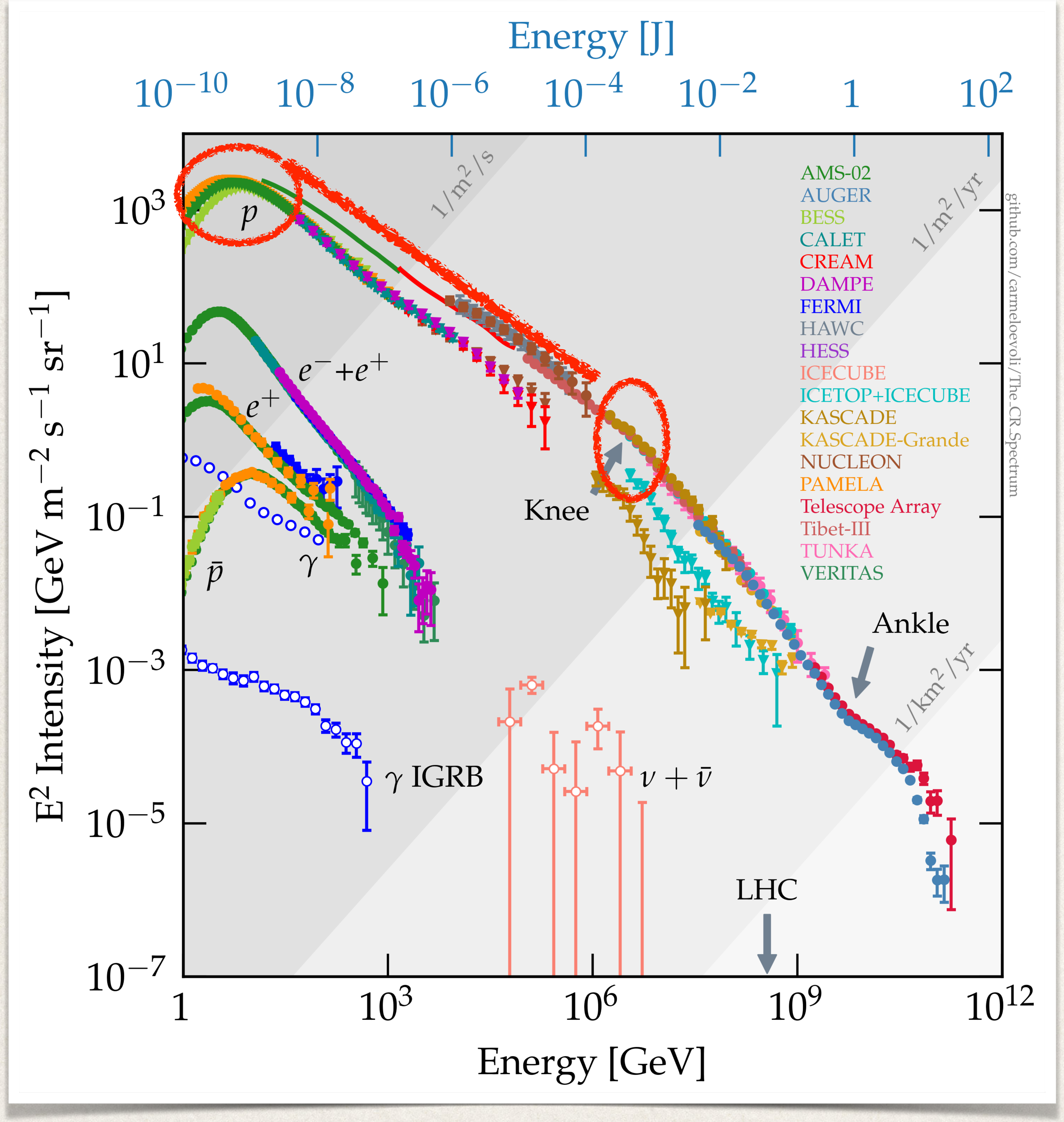

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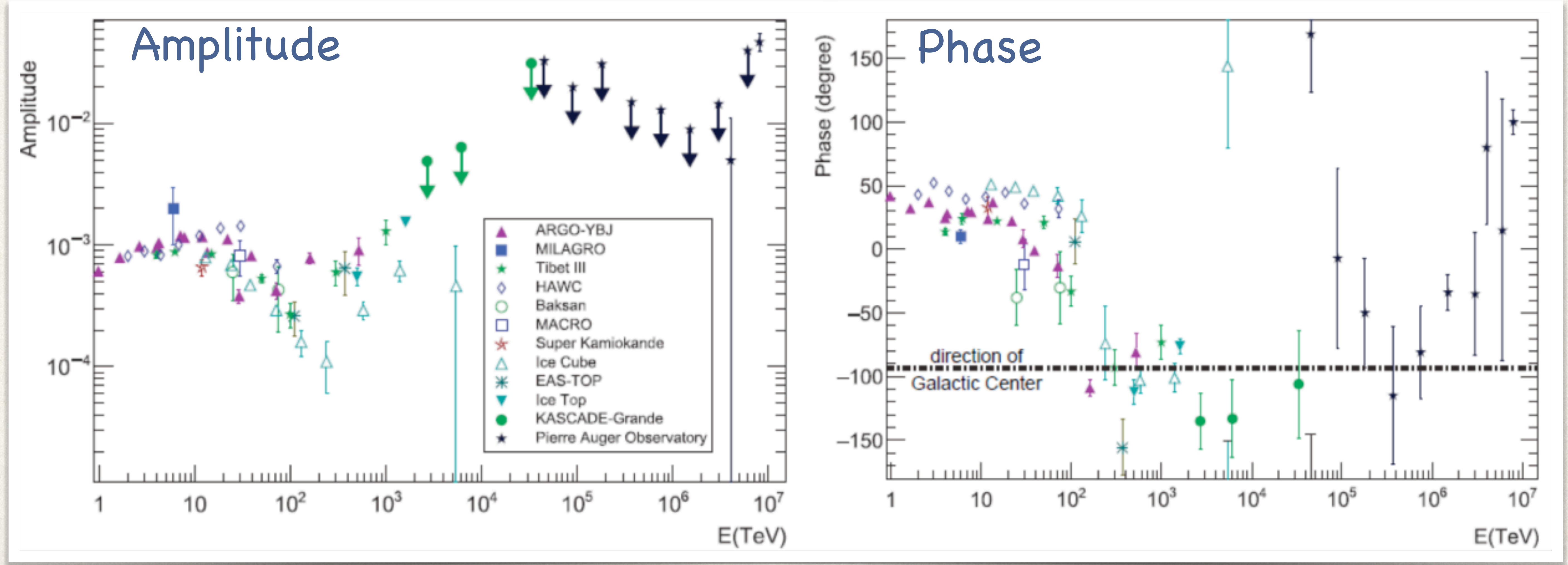

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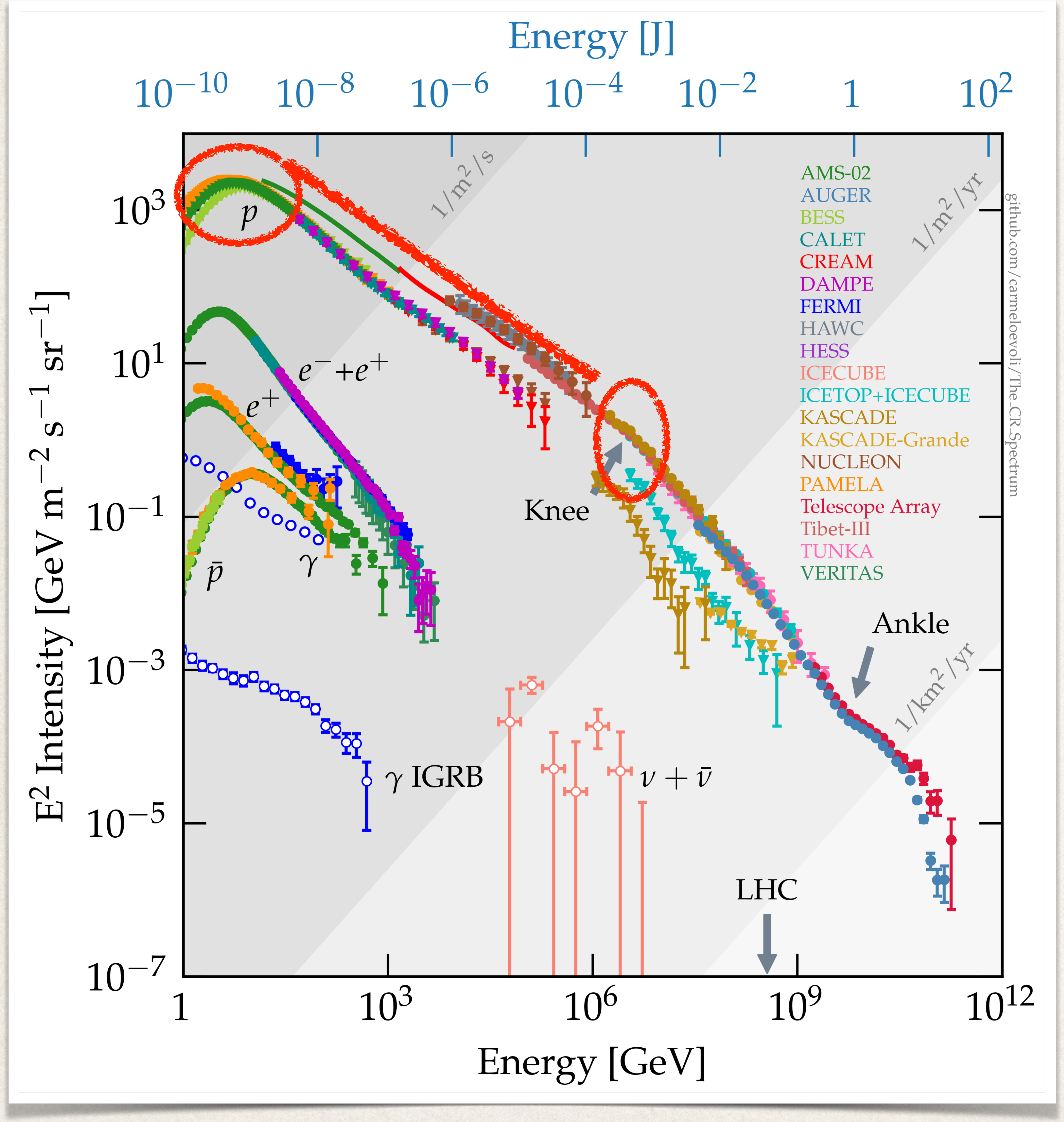

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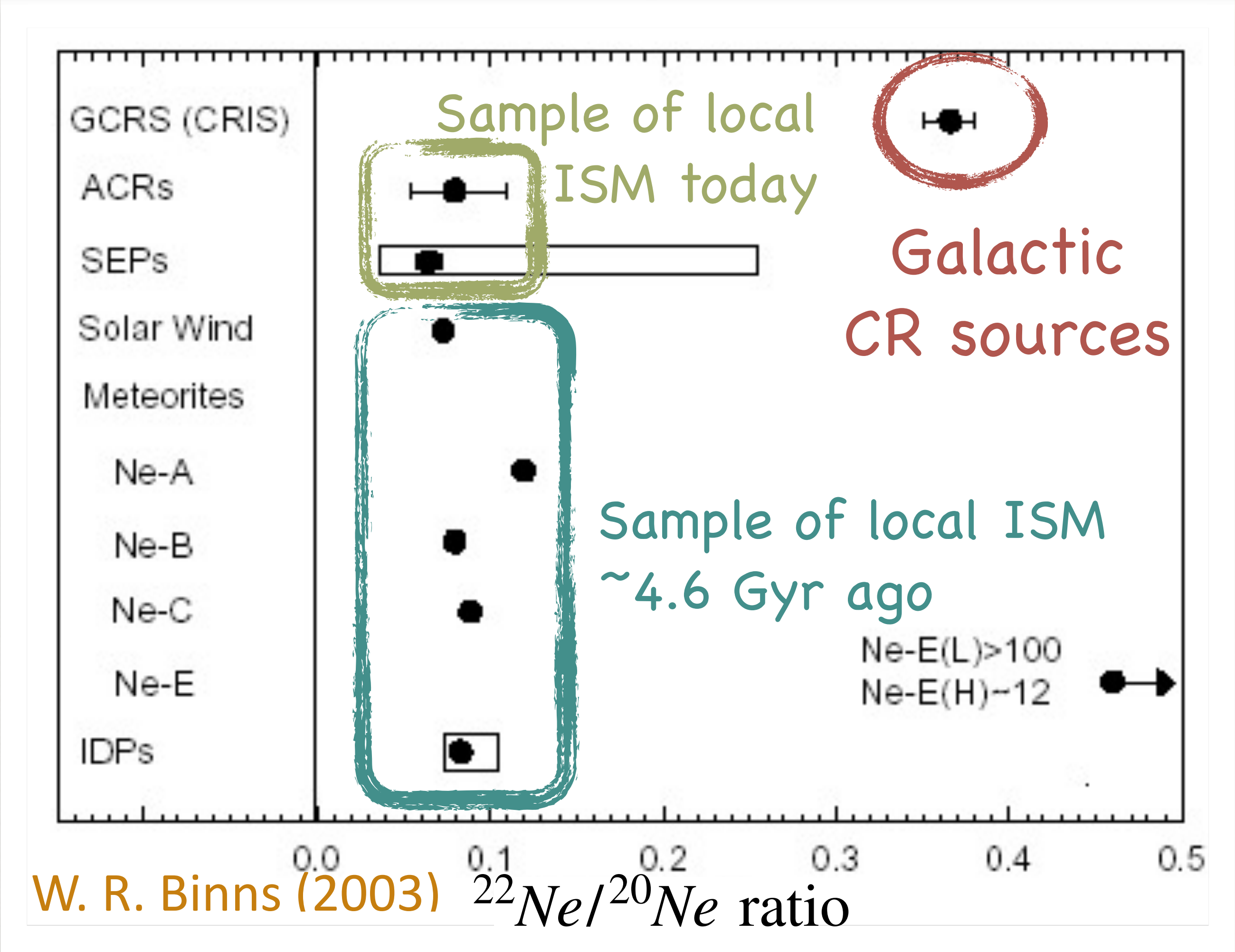
- **Composition:** few anomalies w.r.t. Solar



W. R. Binns (2003)

^{22}Ne / ^{20}Ne ratio

The SNR paradigm for the origin of CRs

Why SNR are so popular?

- Enough power to supply CR energy density (~10% of the explosion energy)
- Spatial distribution of SNRs compatible with the CR distribution
- Presence of non-thermal emission in SNRs
- A solid theory (DSA) applicable to SNR shocks

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Unsolved issues:

- No evidence of acceleration beyond ~100 TeV even in very young SNRs
- Predicted gamma-ray spectrum does not match the observed ones
- Escaping from sources not fully understood
- Anomalous CR chemical composition cannot be easily explained
- Spectral anomalies (p, He, CNO have different slopes)

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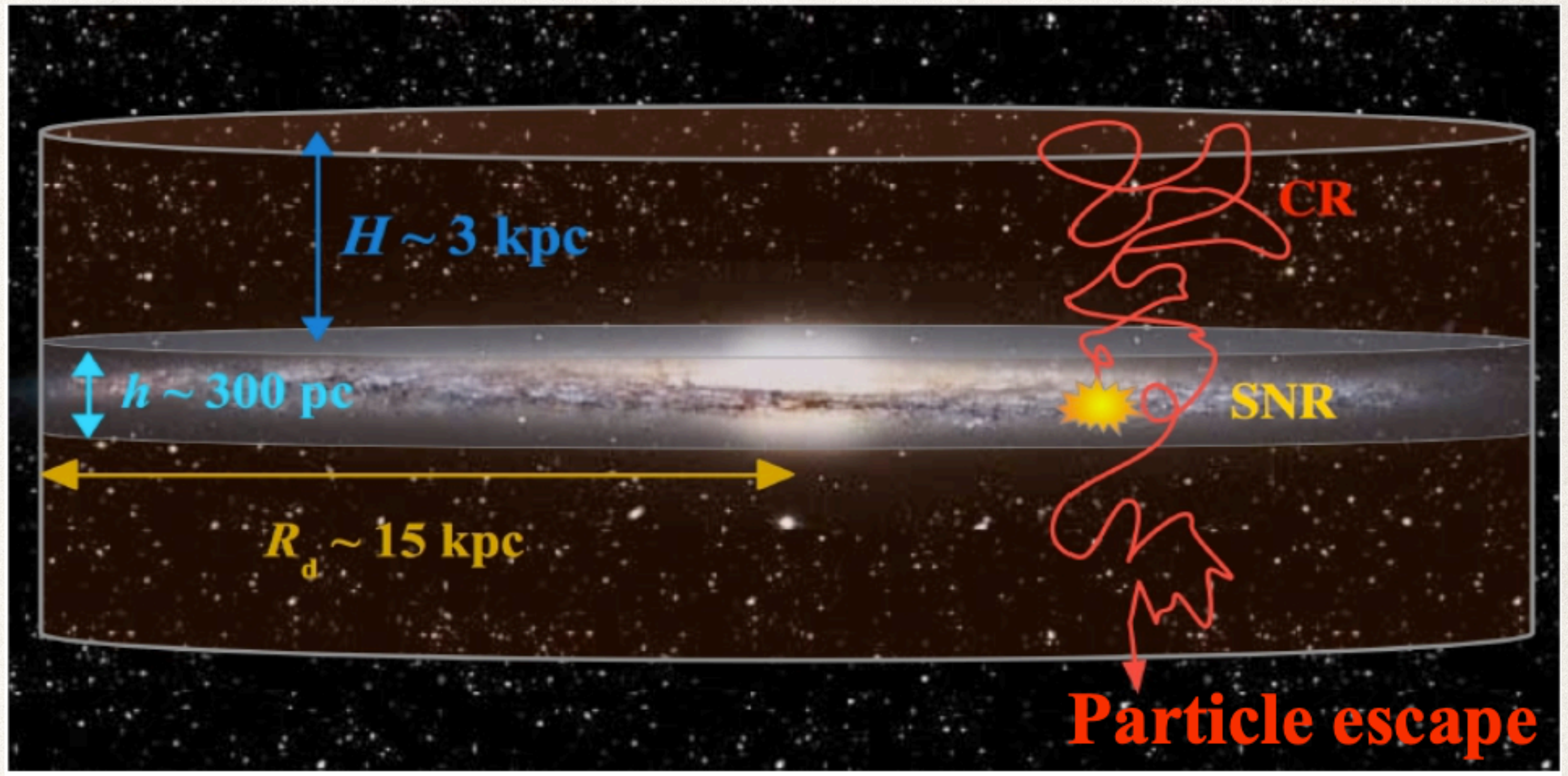
The Galactic propagation model

Ginzburg & Syrovatskii (1964)

The basic picture



- CRs diffuse in a magnetic halo larger than the Galactic disk
- CRs freely escape from the halo boundary (from Beryllium data $H \gtrsim 5\,\mathrm{kpc}$)
- Spallation occurs in the Galactic disc
- Injection from SNR as power law: $Q_{\rm inj}(R) \propto R^{-\gamma_{\rm inj}}$
- The diffusion coefficient D(E) is assumed constant everywhere in the halo:

$$D(R) = \beta D_0 \frac{(R/\mathrm{GV})^{\delta}}{\left[1 + (R/R_b)^{\Delta s/s}\right]^{s}}$$

- CR advect along z direction: $u_{\rm adv}$

Fitting primary CR and secondary/primary →

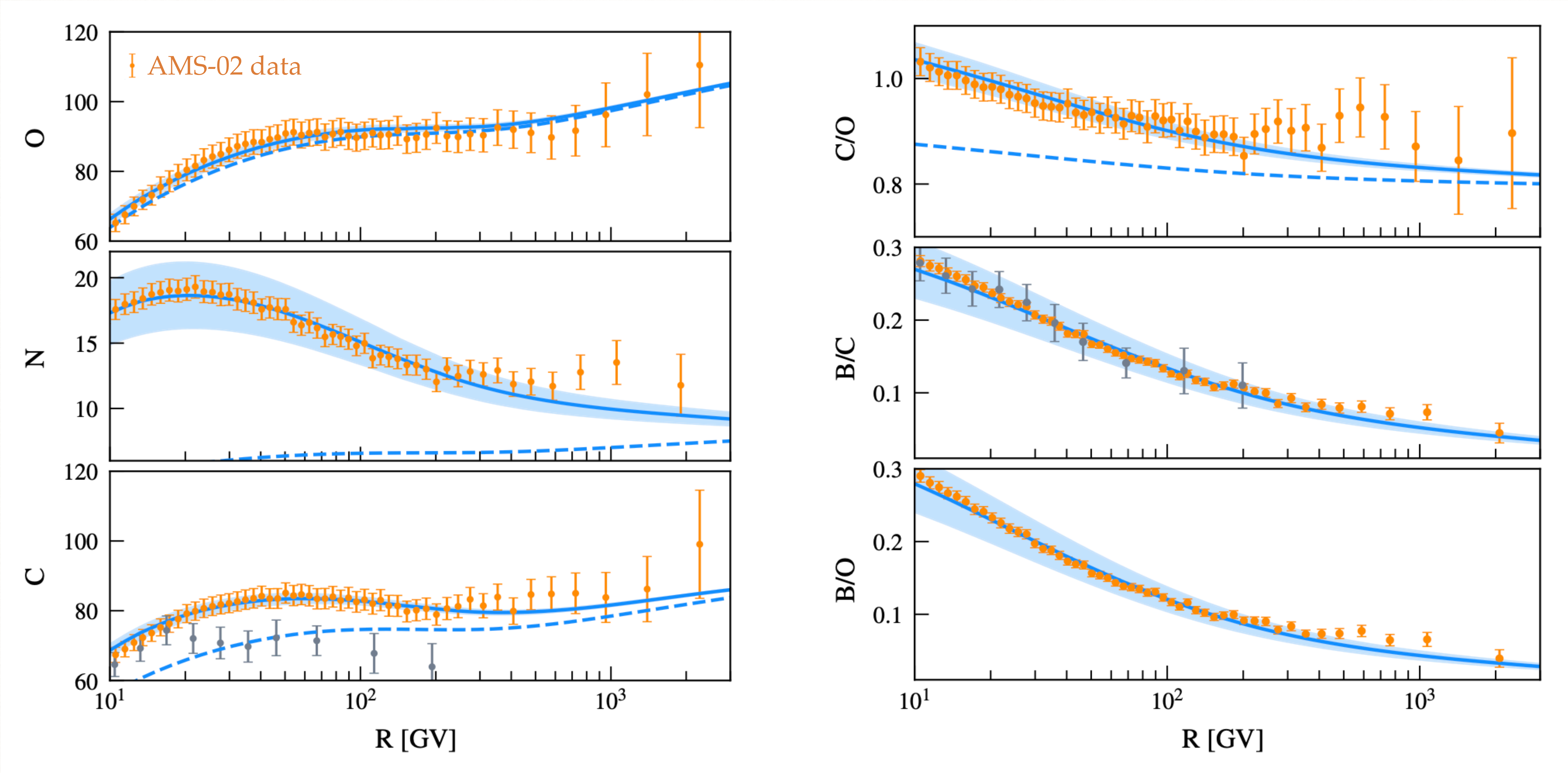
$u_{\rm adv}$
$D(R)\ [D_0\,\delta\,, s]$
$\gamma_{\rm inj}$

Spectra of primary Cosmic Rays

[Evoli, Aloisio, Blasi, PRL 2019]

Heavy elements (CNO) can be fitted with identical injection spectrum determining the Galactic diffusion properties (grammage)

$$Q_{\rm inj} \propto p^{-\gamma} \qquad \gamma_{\rm CNO} = 4.26$$



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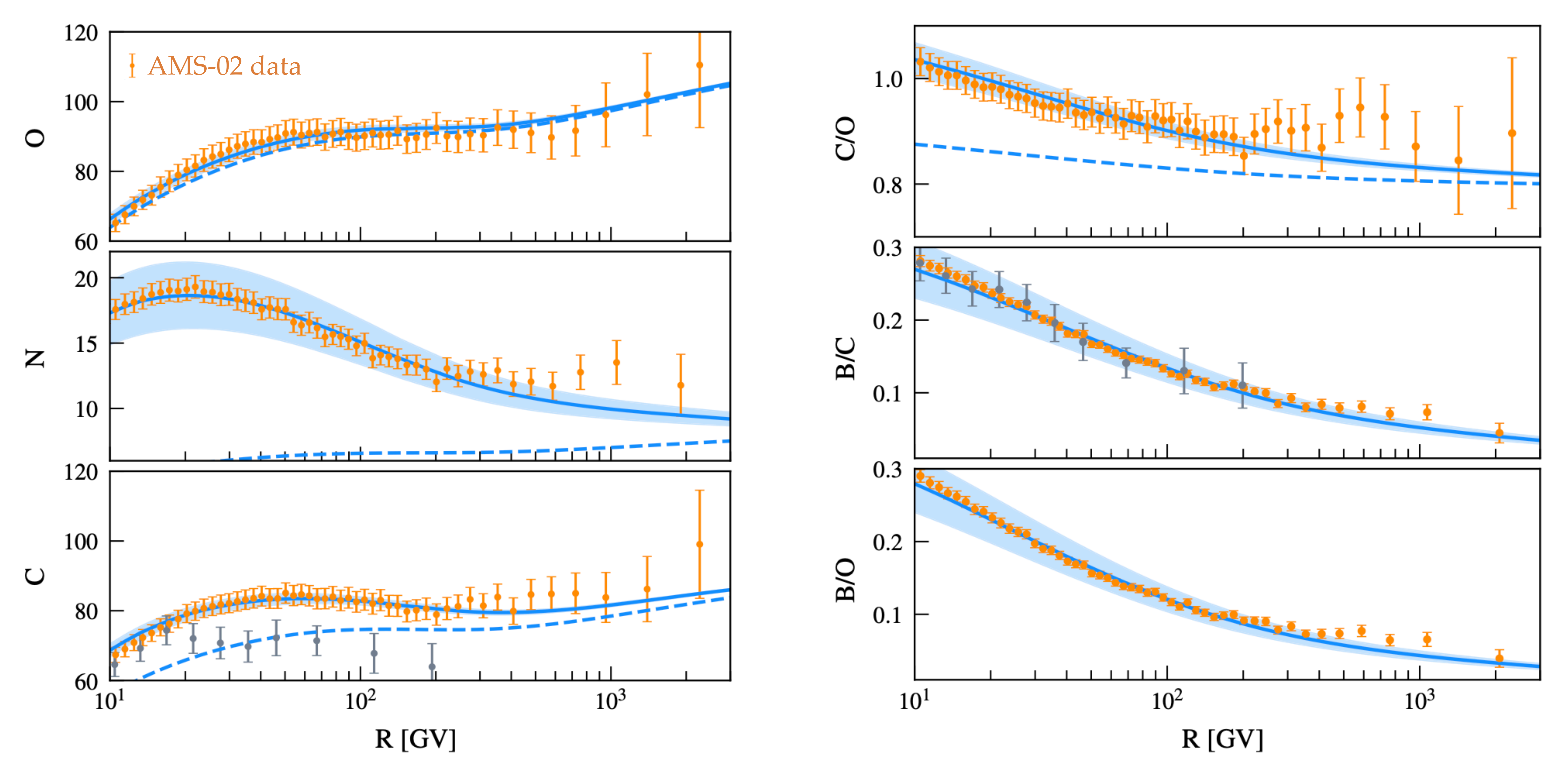
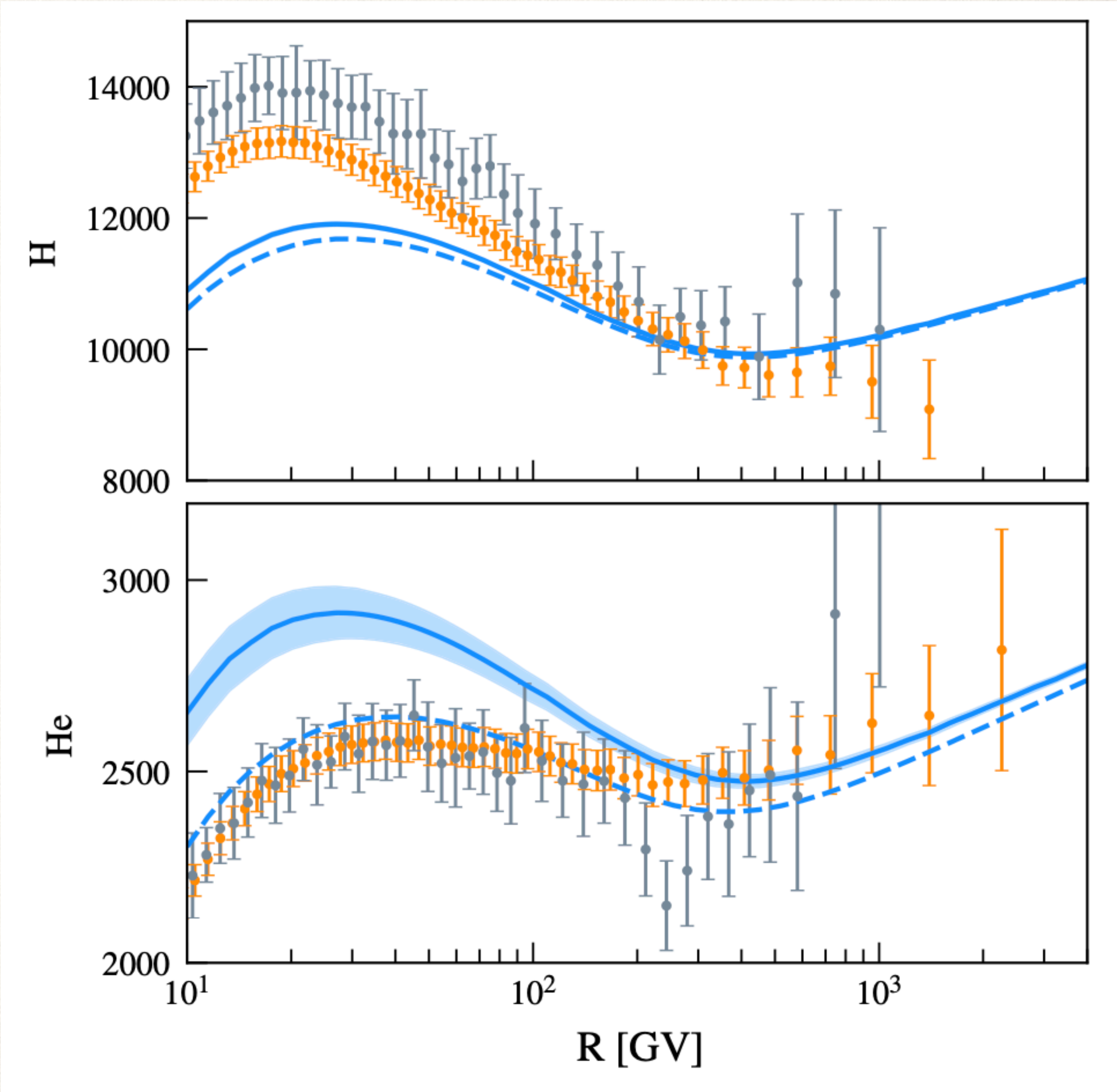
H and He requires
different slopes

$\gamma_{\rm H} = 4.31, \;\; \gamma_{\rm He} = 4.21$





$\Delta\gamma_{\rm H-He} \simeq 0.1$

Spectra of primary Cosmic Rays

[Evoli, Aloisio, Blasi, PRL 2019]

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determini

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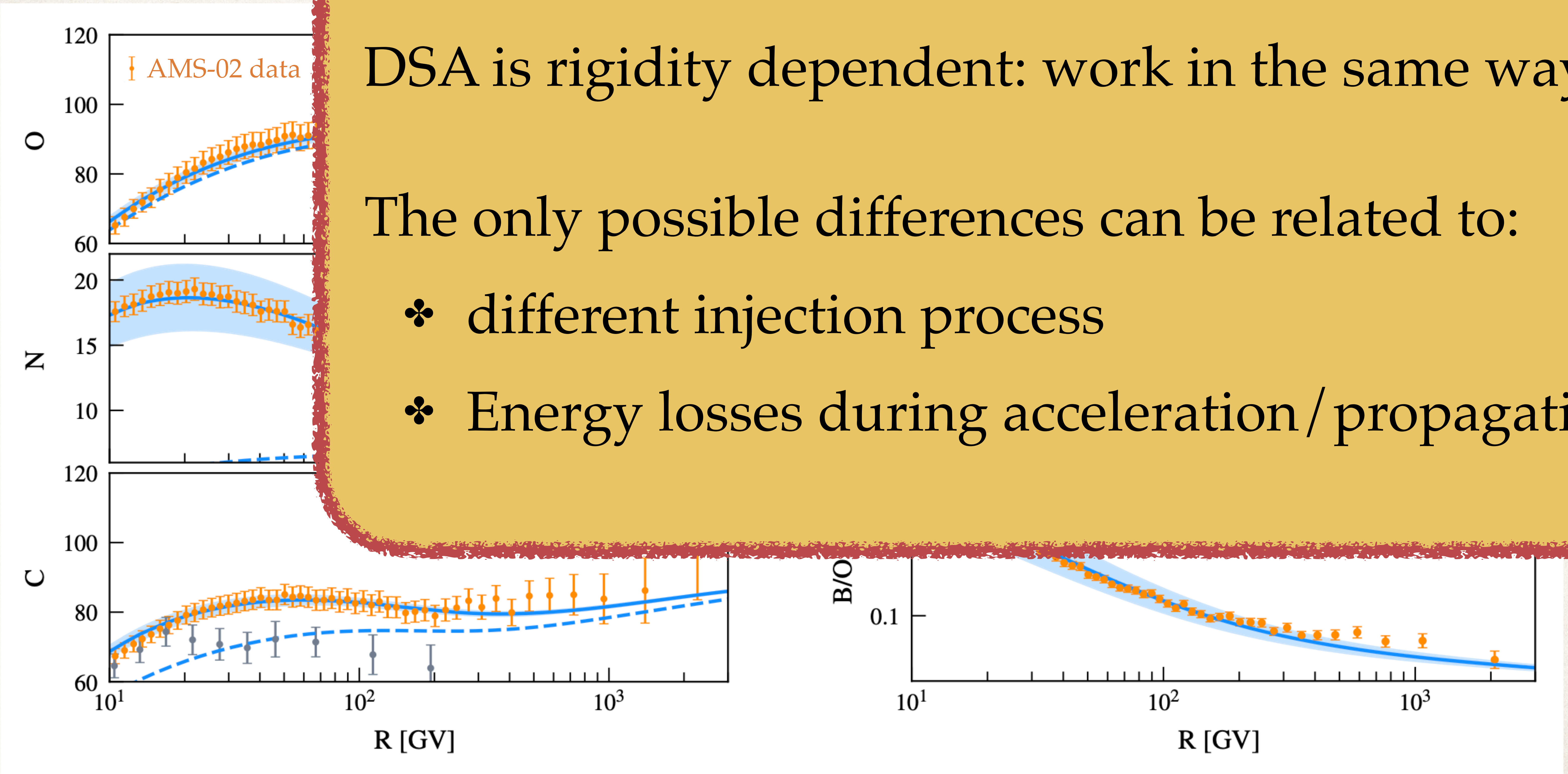
, $\gamma_{\mathrm{He}} = 4.21$

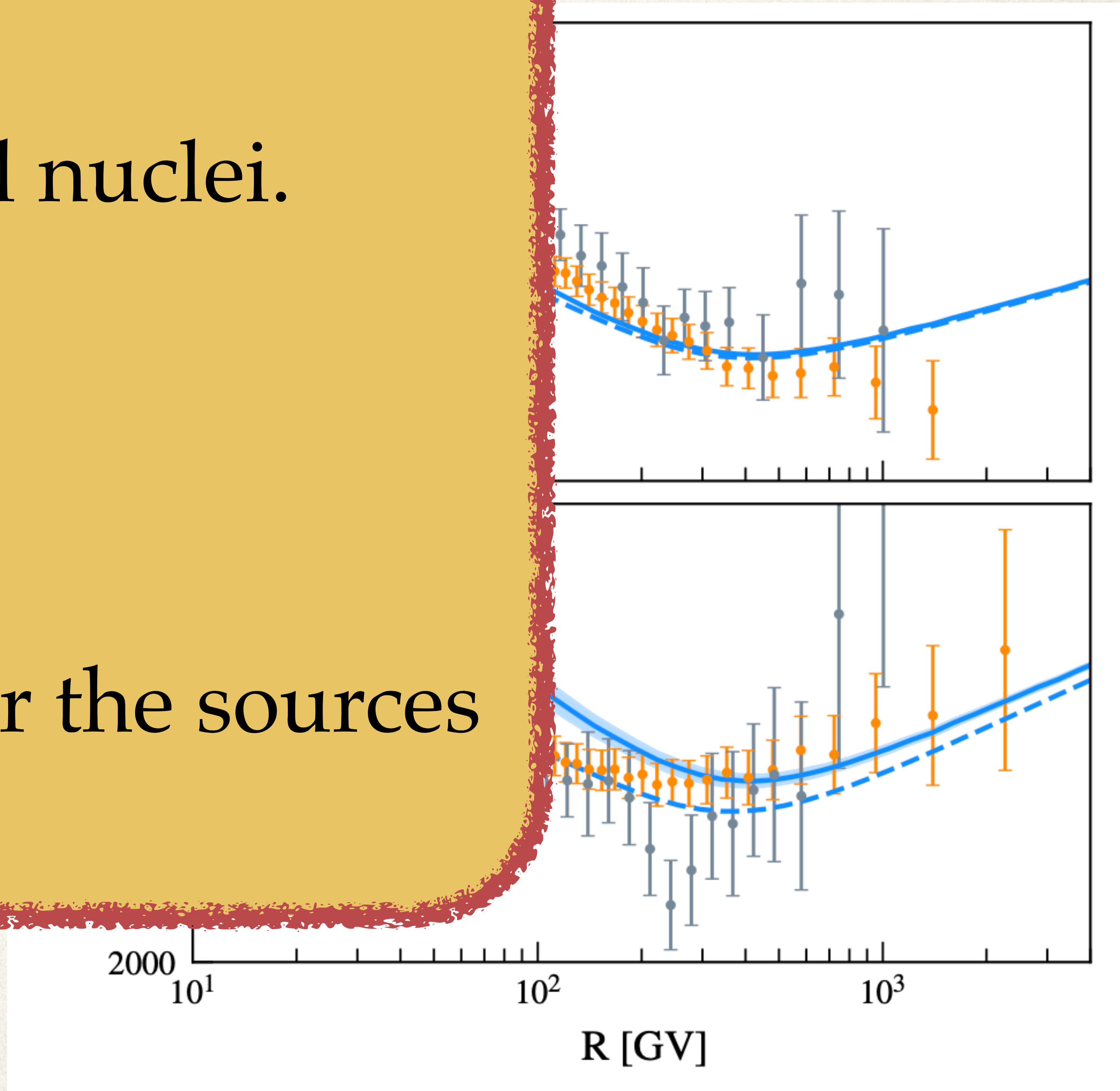
How can we explain the difference between H and He and CNO?

DSA is rigidity dependent: work in the same way for all nuclei.

The only possible differences can be related to:

- different injection process
- Energy losses during acceleration/propagation near the sources





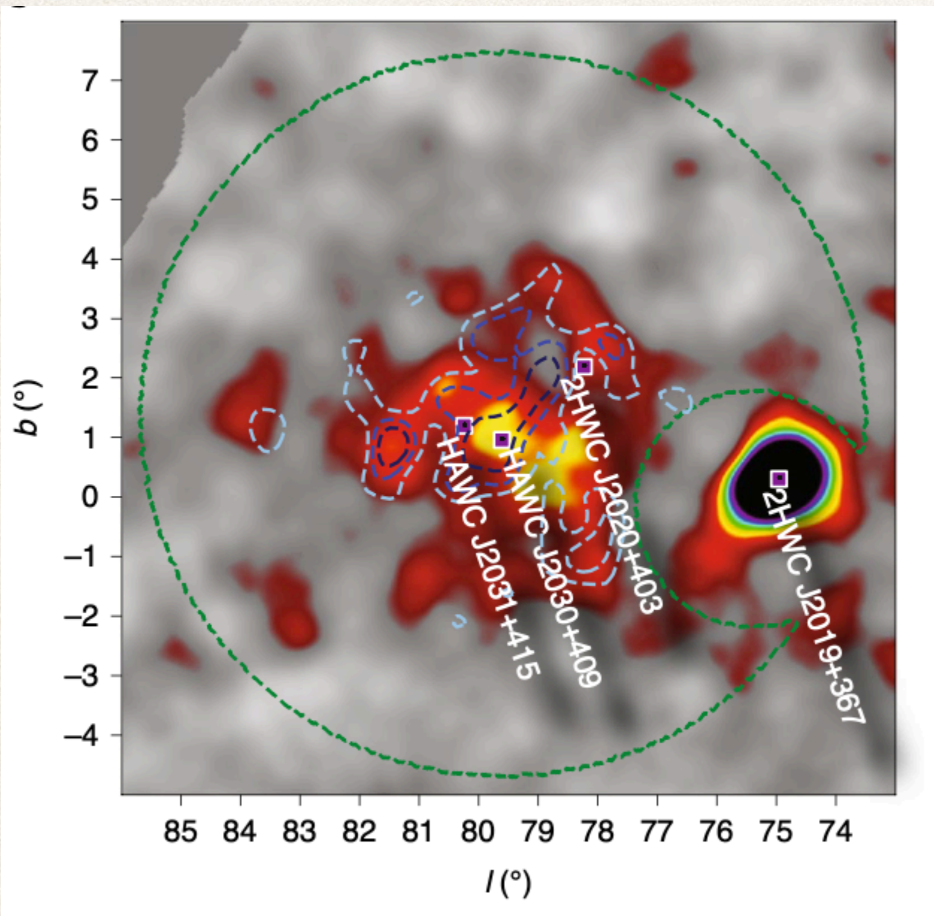
$\Delta\gamma_{\mathrm{H-He}} \simeq 0.1$

What are we missing?

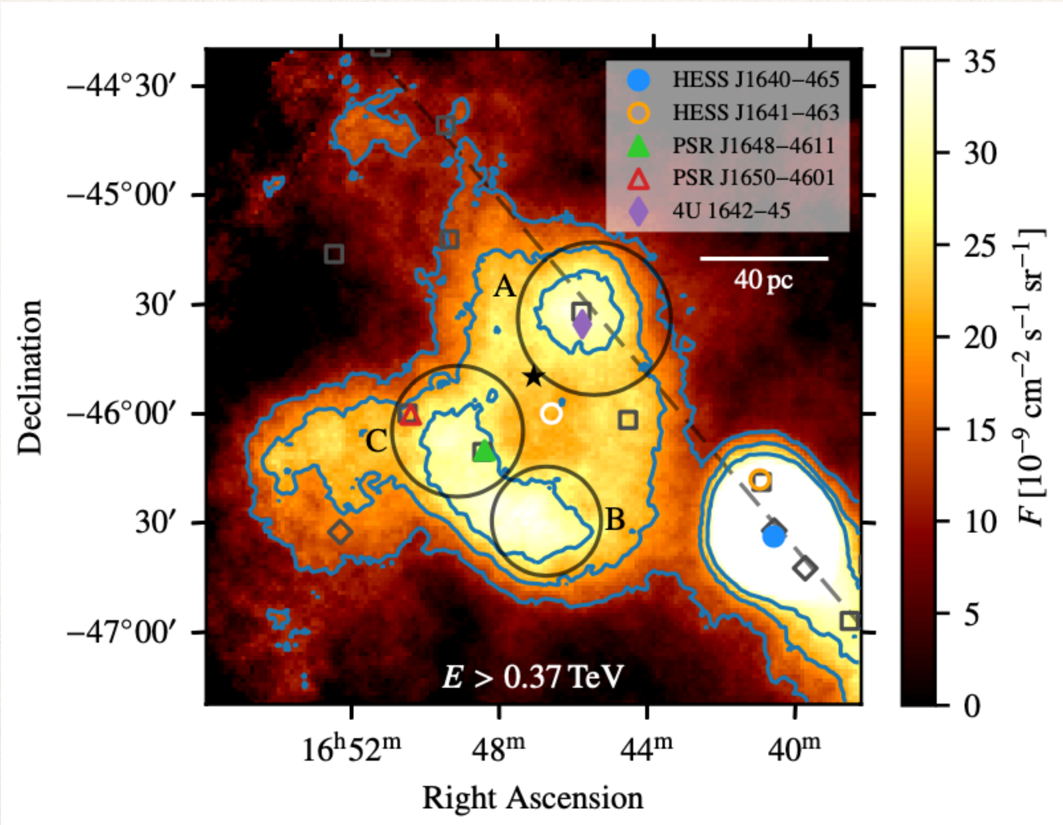
- Particle acceleration models often apply to isolated SNRs (OK for type Ia SNe)

- However the majority of massive stars born in Star Clusters
  - **~80%** of Core-Collapse SNe explode in SCs
  - **~20%** explode as isolated (probably associated to runaway stars)

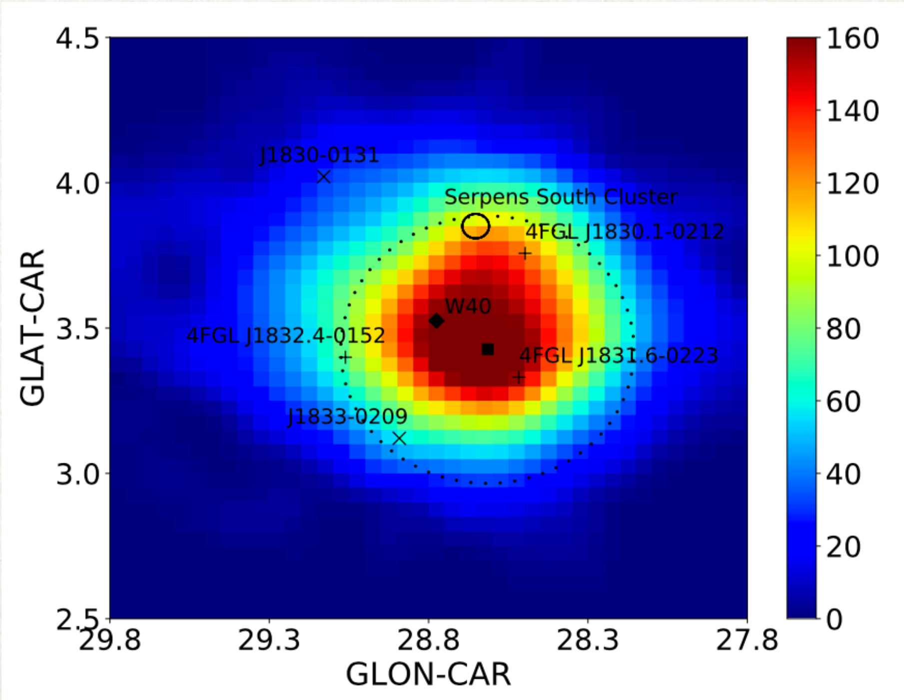
- Several young massive stellar clusters have been associated to diffuse gamma-ray sources



Cygnus OB2
HAWC



Westerlund 1
HESS



W40
Fermi

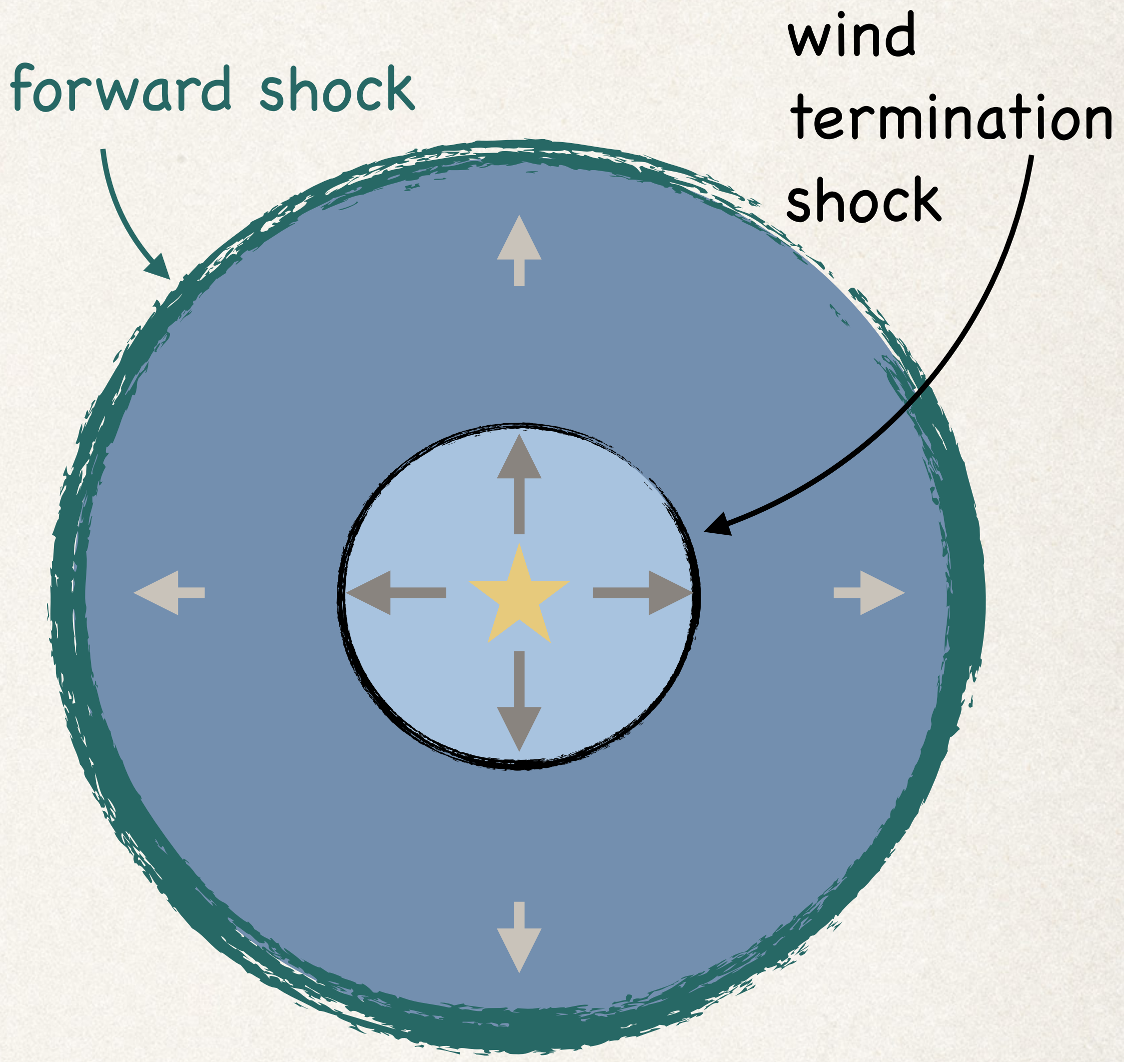
Stellar clusters and super-bubbles (the elephant in the room)

- Stellar winds from massive stars modify the circumstellar environment
  - Lower density ($n \sim 10^{-3} - 0.1$)
  - Higher temperature ($T \sim 10^6 - 10^8\,\mathrm{K}$)
  - Enhanced magnetic turbulence (+ advection)
- Stellar winds produce shocks

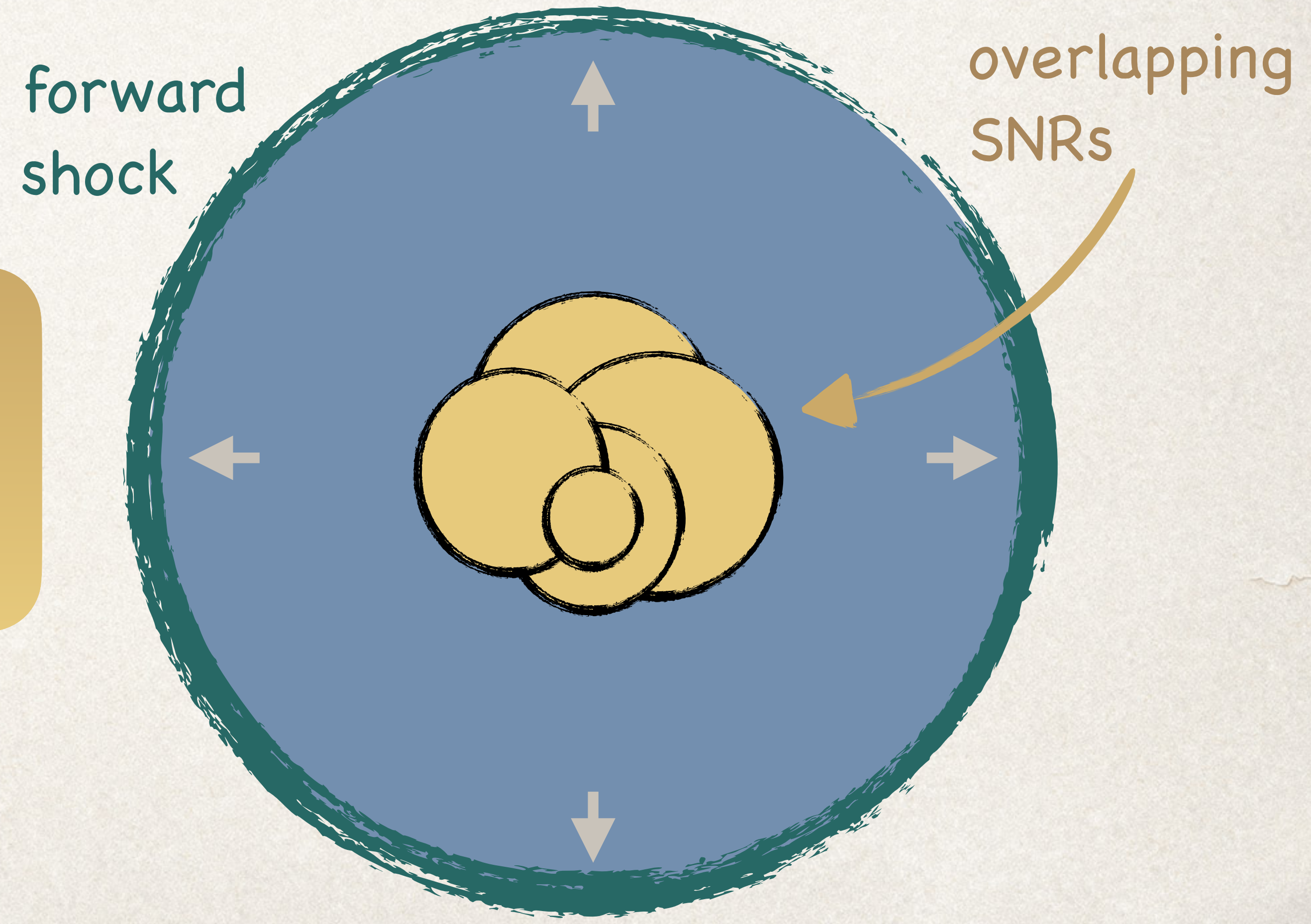
➡ Particle acceleration:

  - Young clusters: at wind termination shock
  - Old clusters: at SNR shocks (in modified environment)

$t \lesssim 3\,\mathrm{Myr}$
only stellar winds



$3\,\mathrm{Myr} \lesssim t \lesssim 30\,\mathrm{Myr}$
stellar wind + SNe



Particle acceleration at the wind termination shock

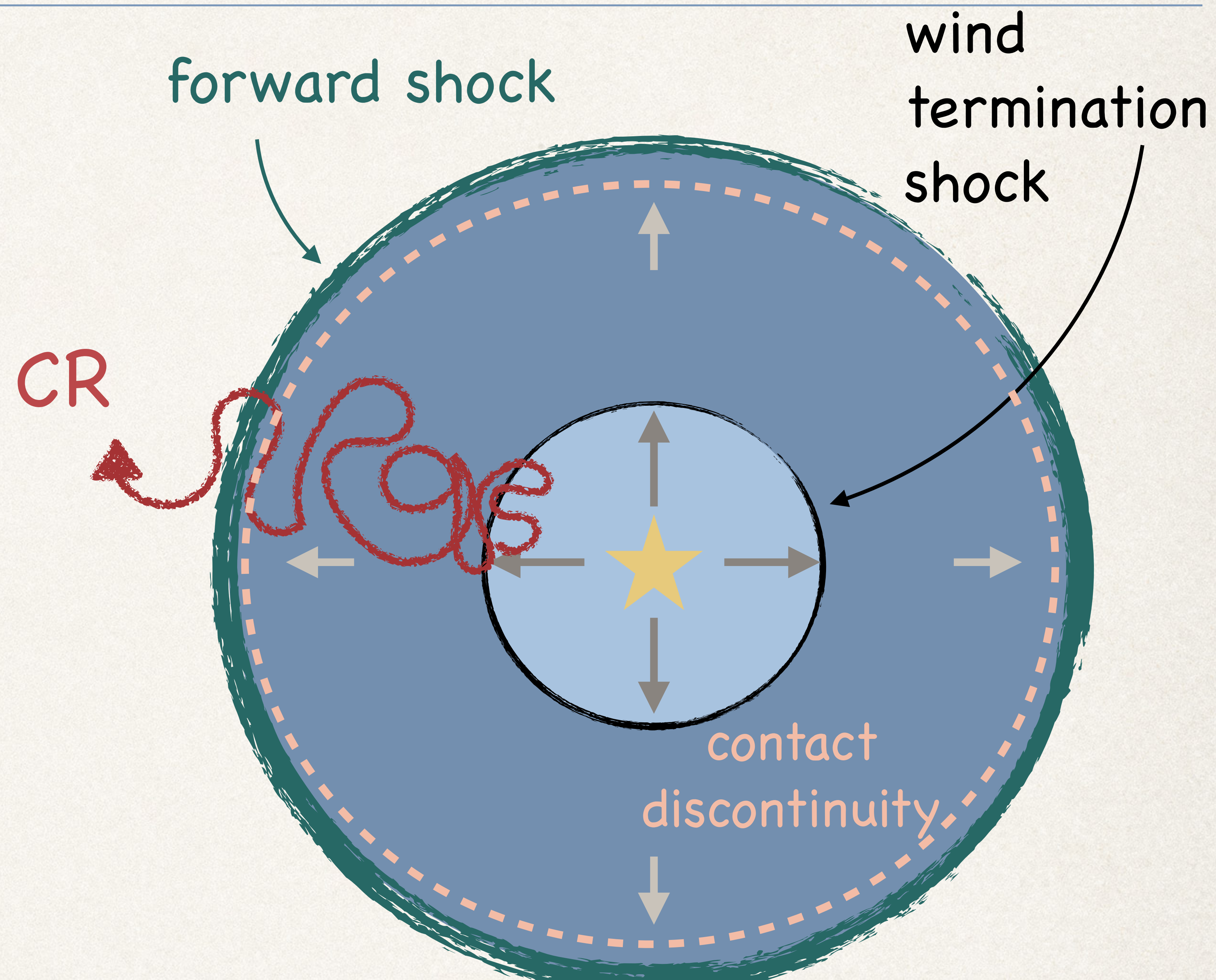
GM, Blasi, Peretti & Cristofari (2019)

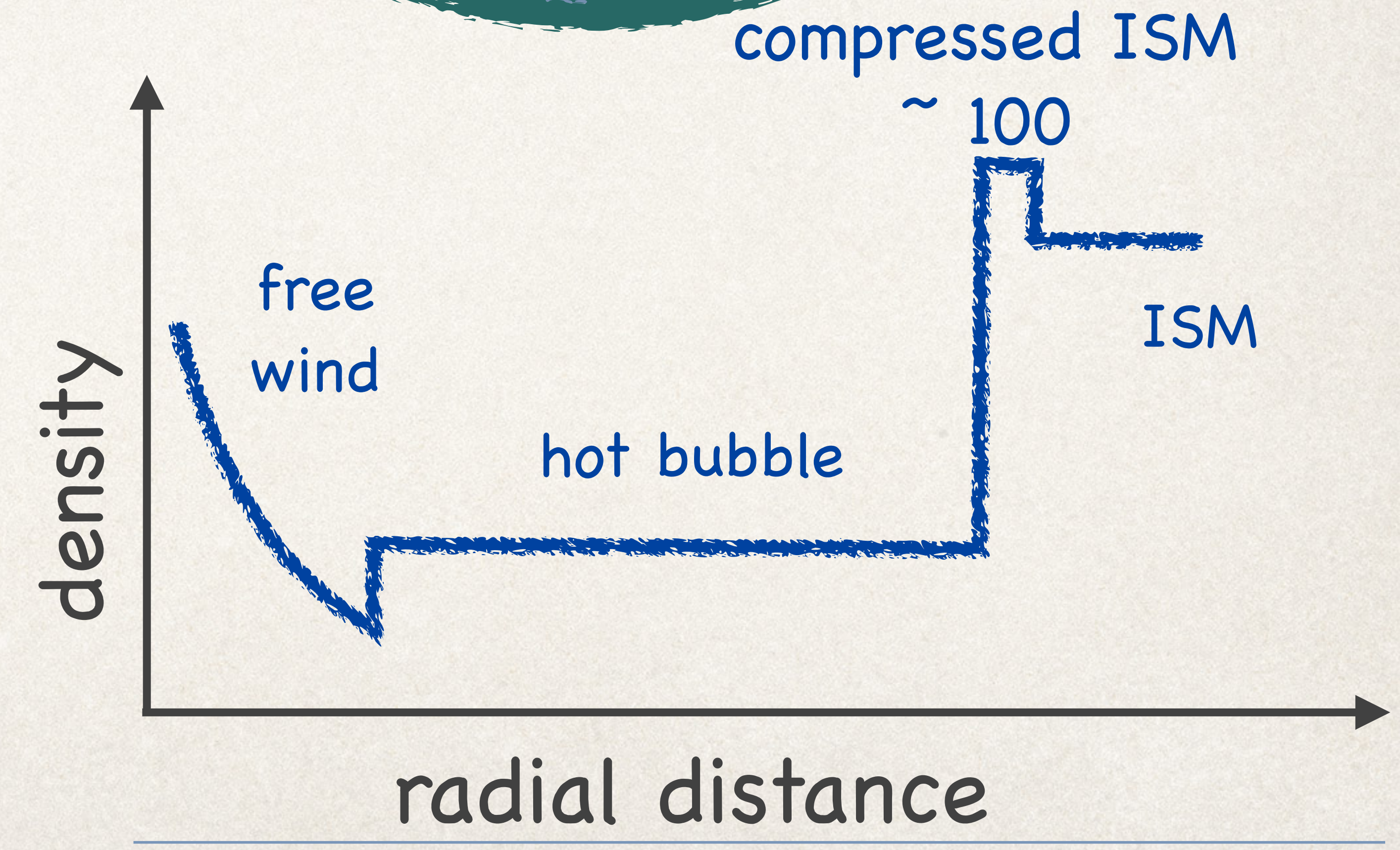
- **Time-stationary transport equation in spherical geometry**
- **Particle injection at the termination shock**
- **Wind velocity profile form adiabatic bubble**
- **Arbitrary diffusion coefficient:**
  - Few % of wind kinetic energy converted into magnetic energy

➡ **Solution at the shock:**

$$f_s(p) = s\frac{\eta_{\rm inj}\, n_1}{4\pi\, p_{\rm inj}^3}\left(\frac{p}{p_{\rm inj}}\right)^{-s} e^{-\Gamma_1(p)}\;\; e^{-\Gamma_2(p)}$$

What about the grammage traversed in the thick shell?

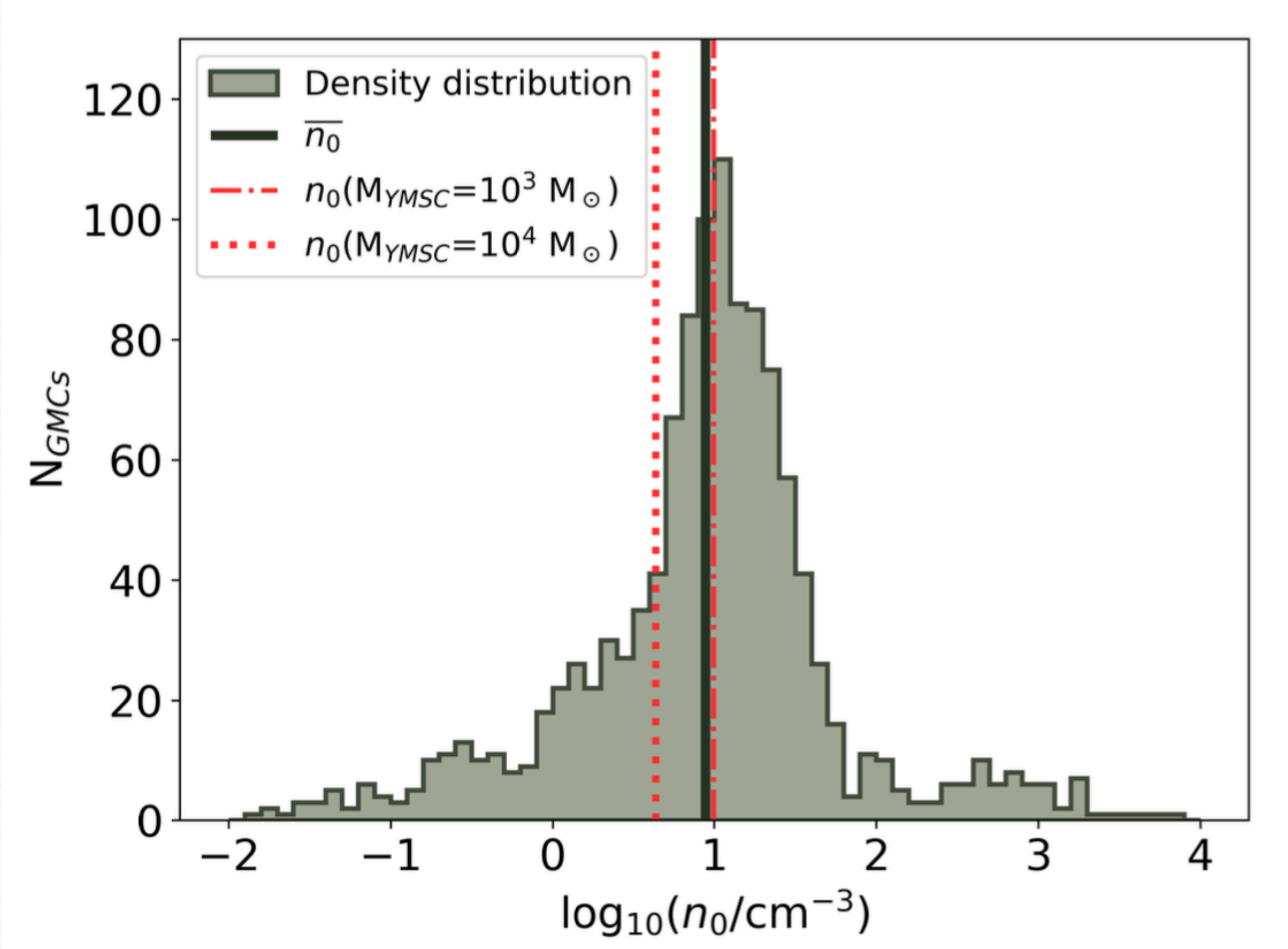




Gas density

Giant molecular clouds

$$\bar{n} \simeq 10 \text{ cm}^{-3}$$



Particle density distribution in Giant Molecular Clouds [Hou & Han, 2014]

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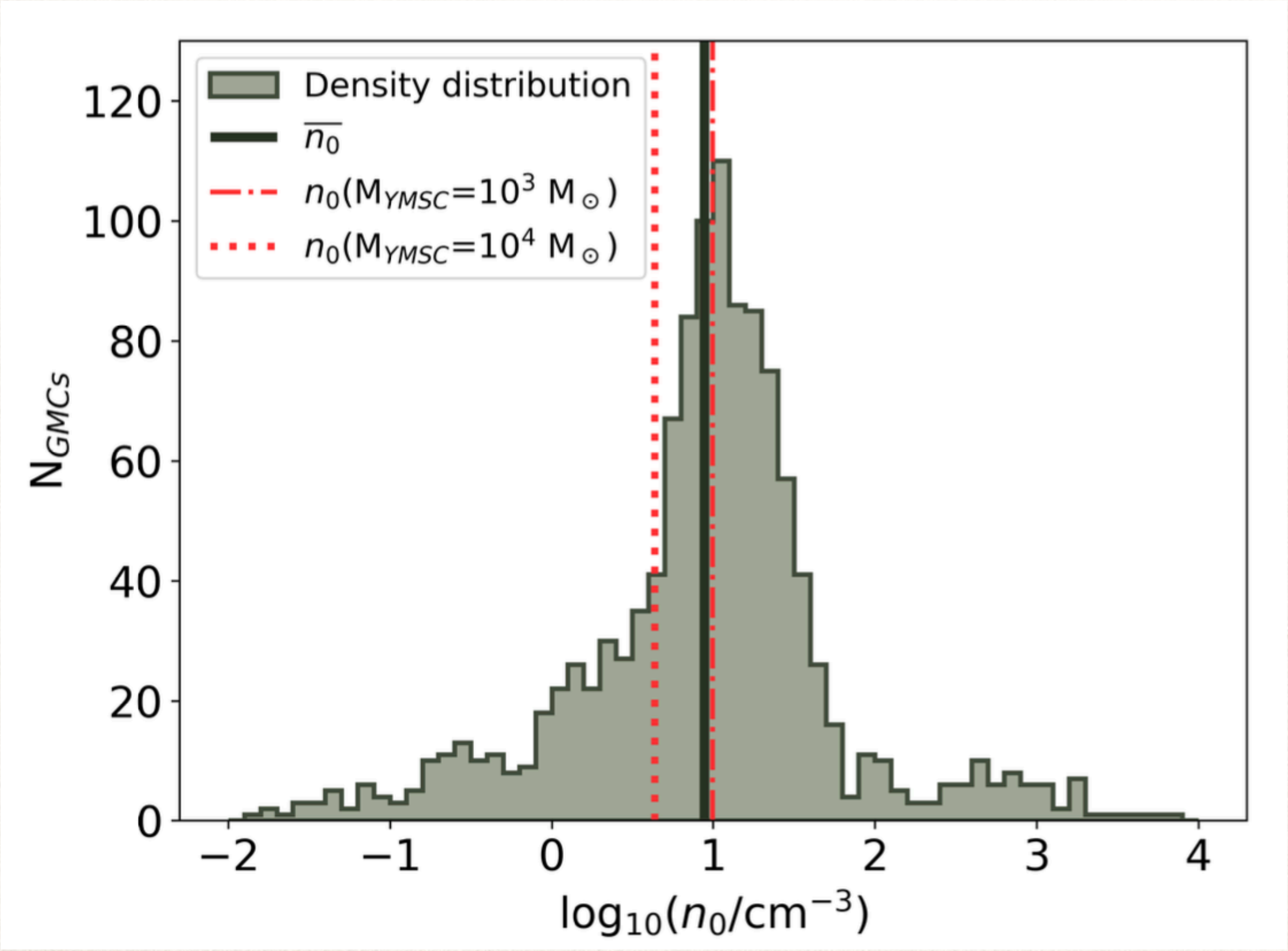

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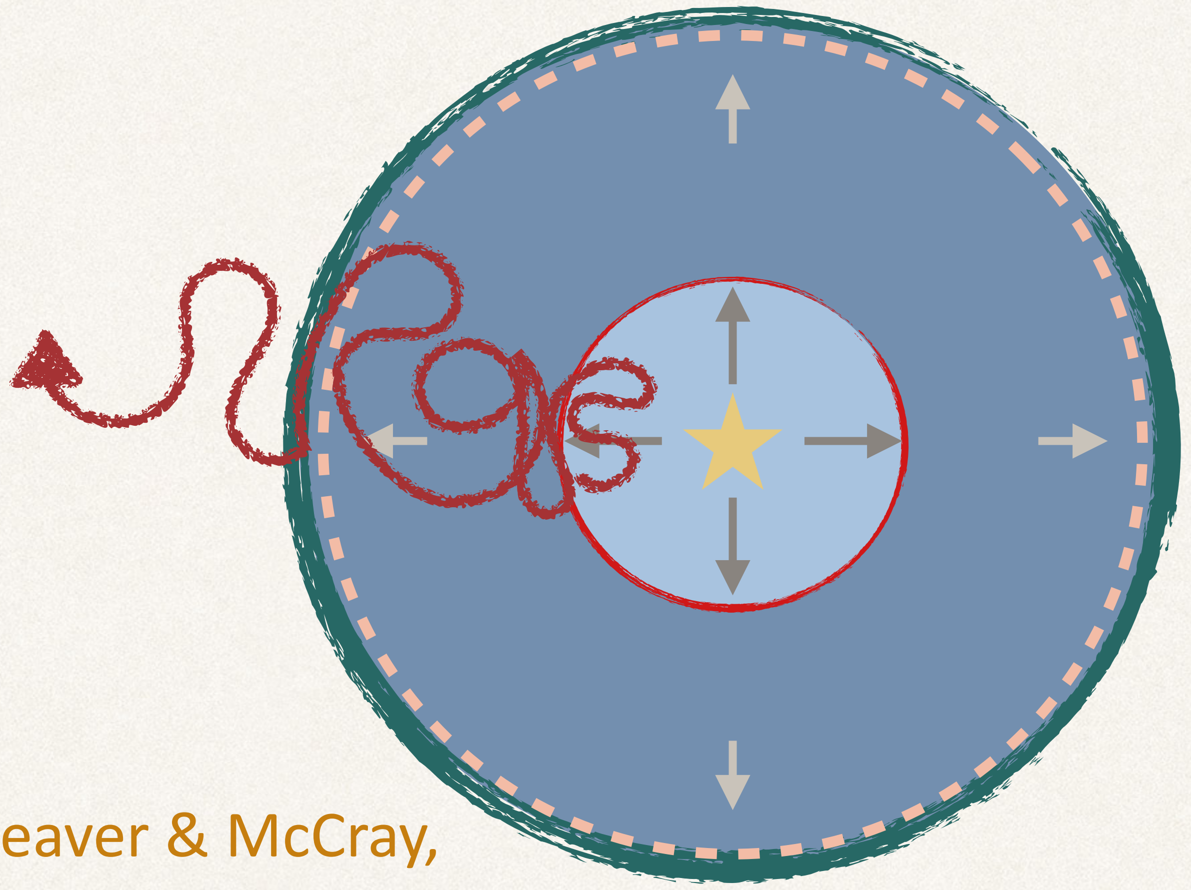
Idealised wind-blown bubble



Weaver & McCray, ApJ 218 (1977)

Average density small if diffusion outside the bubble is fast

$\langle n \rangle \simeq 10^{-2}\ \mathrm{cm}^{-3}$

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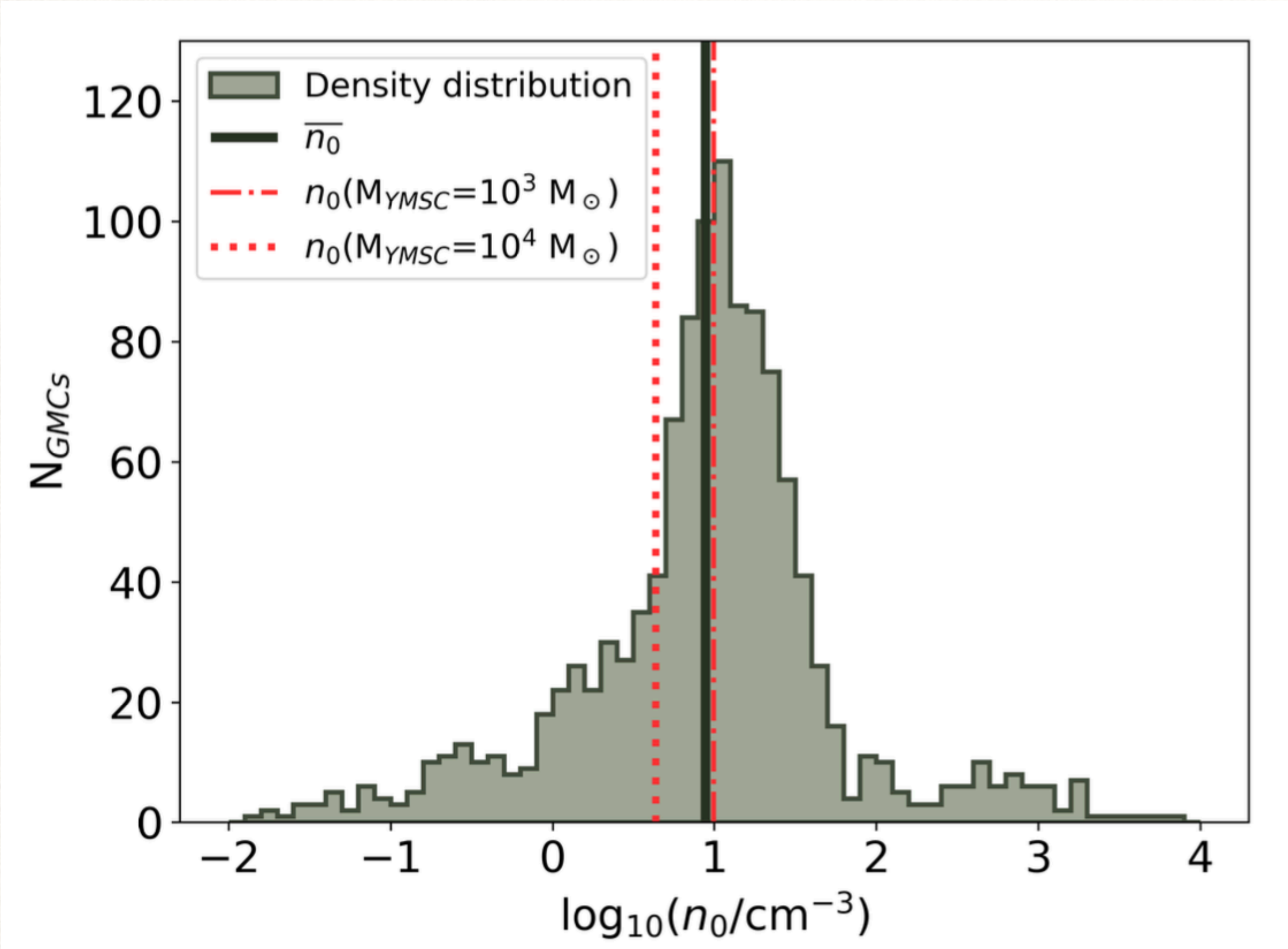

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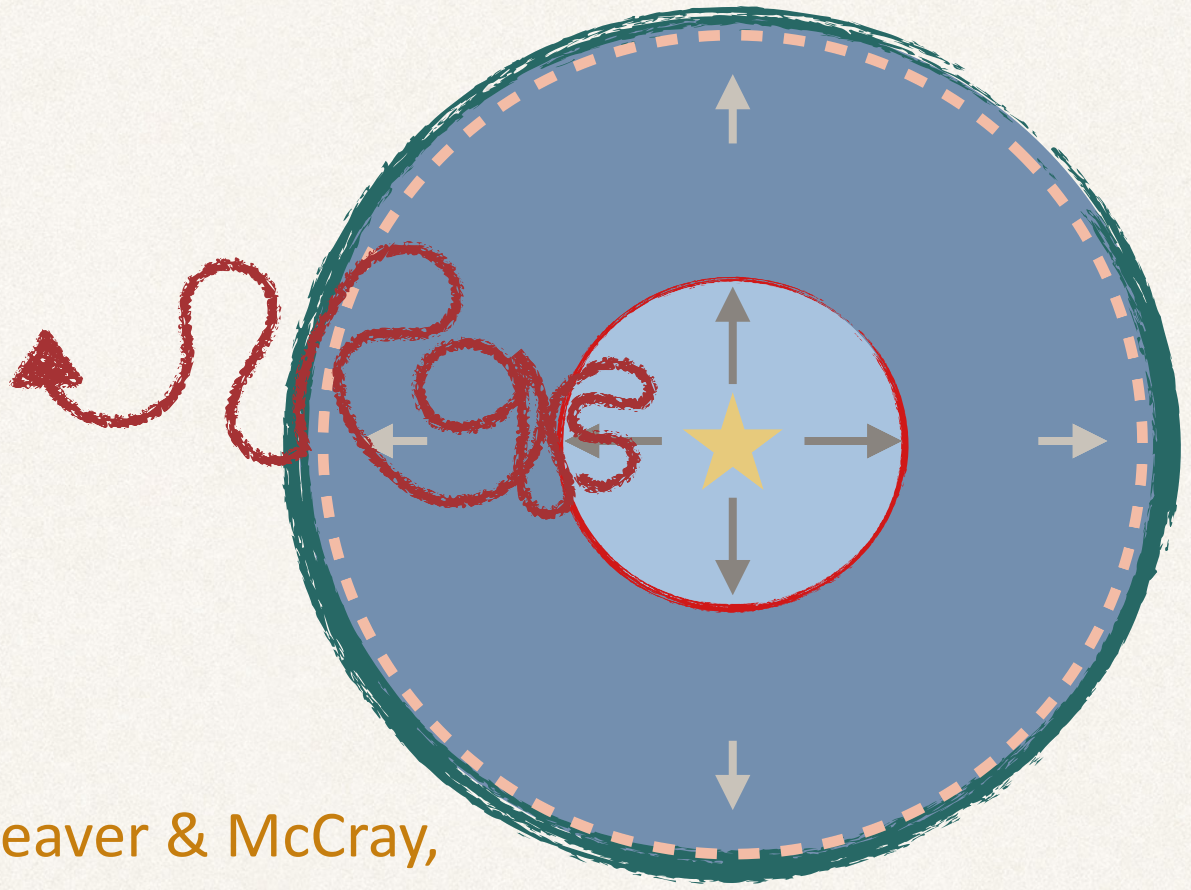

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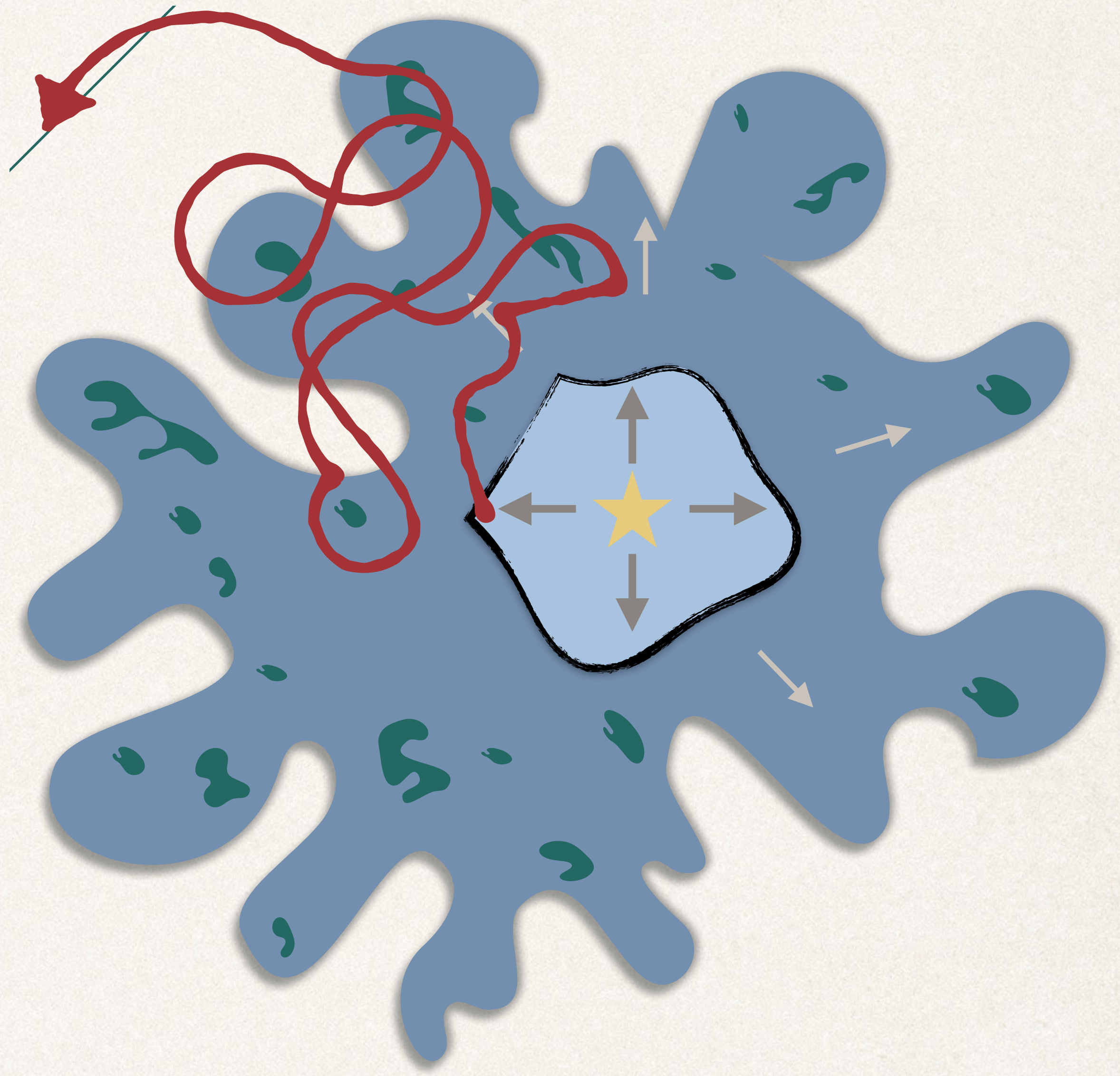
Fragmented wind bubble



Average density felt by diffusing particles
→ depends on the clump distribution
And by diffusion around each clump

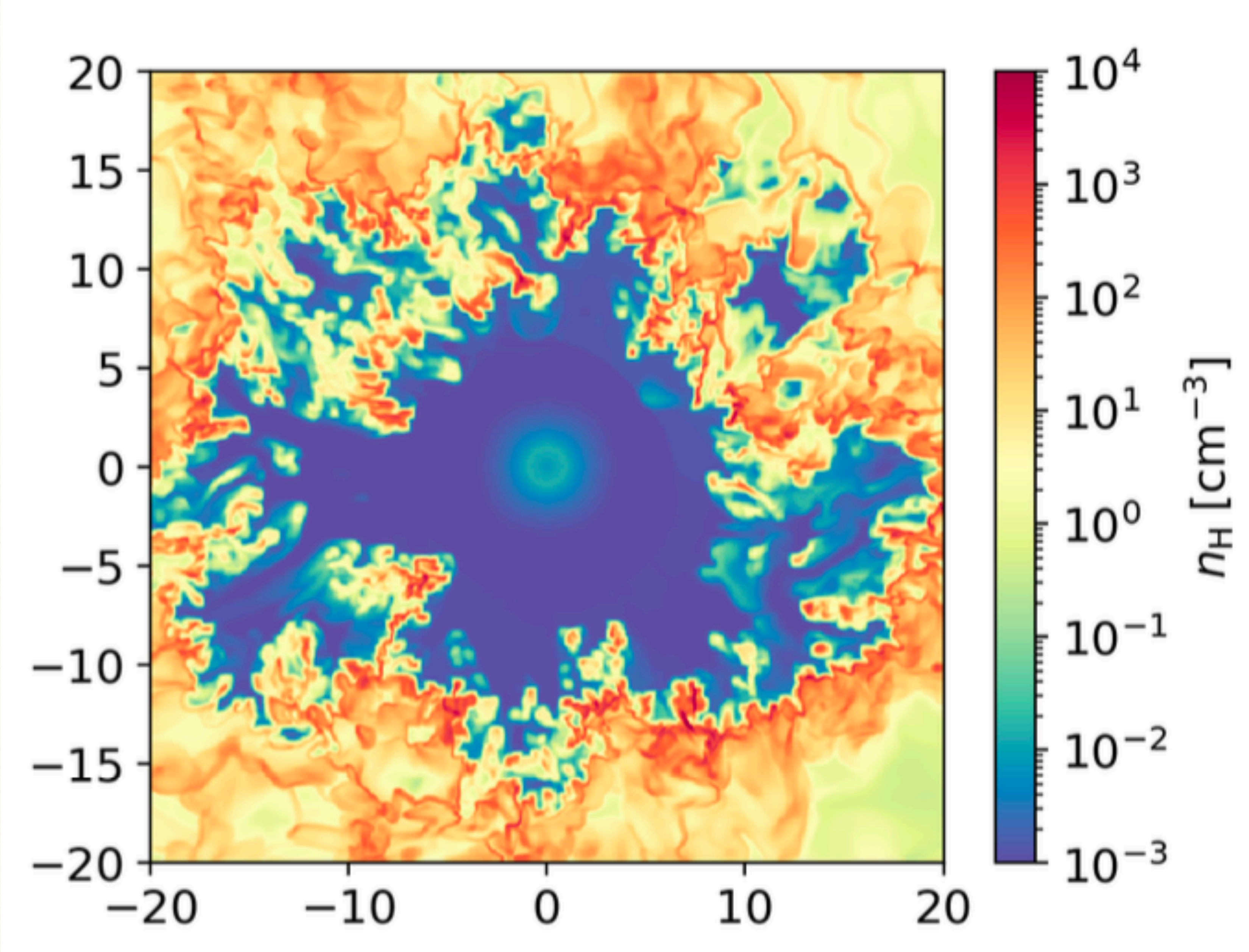
$\langle n \rangle \simeq 10\ \mathrm{cm}^{-3}$

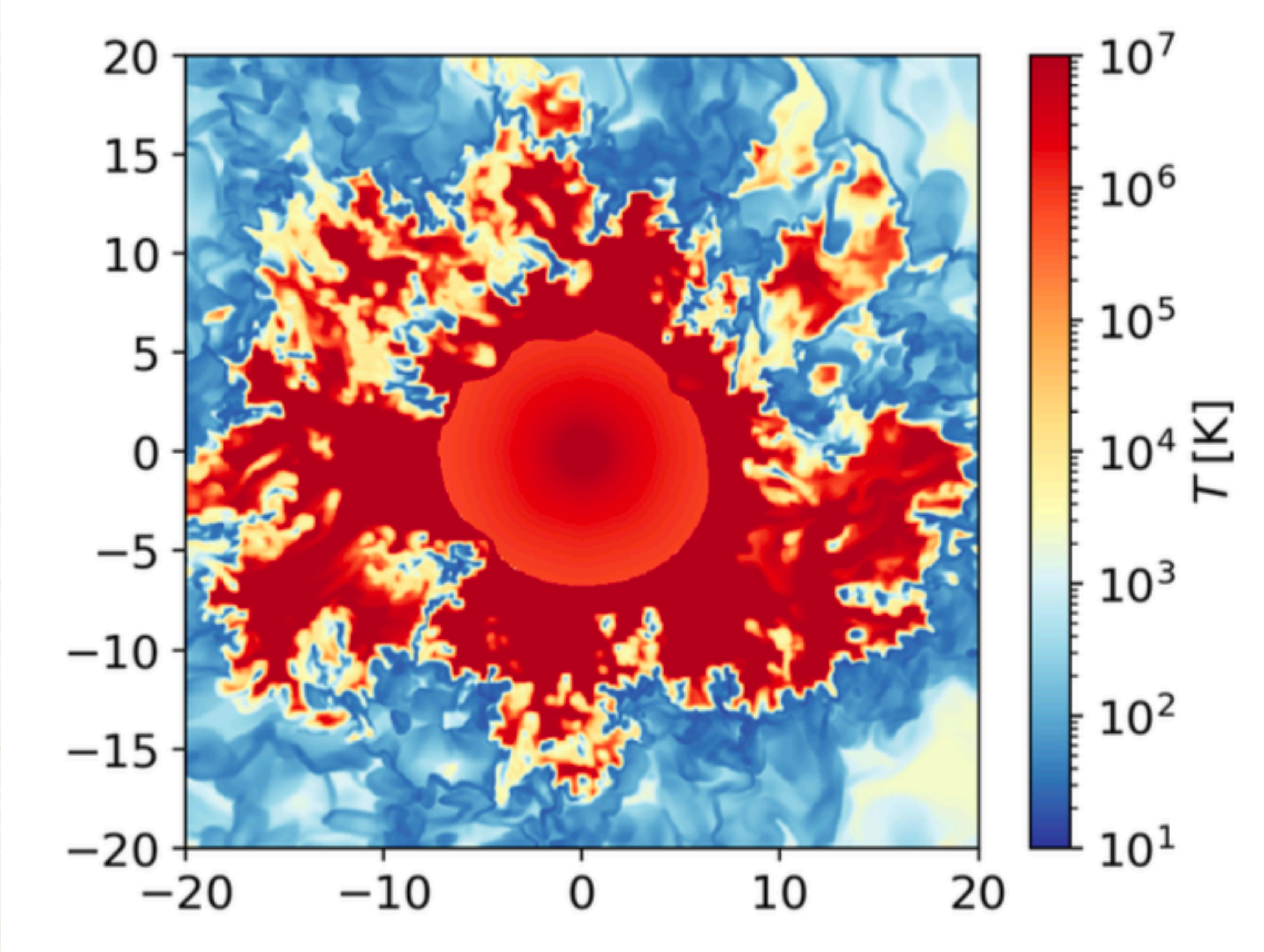
Shell fragmentation as seen in simulations

The dense shell fragments due to

1. Rayley-Taylor instability
2. Radiative cooling

Density



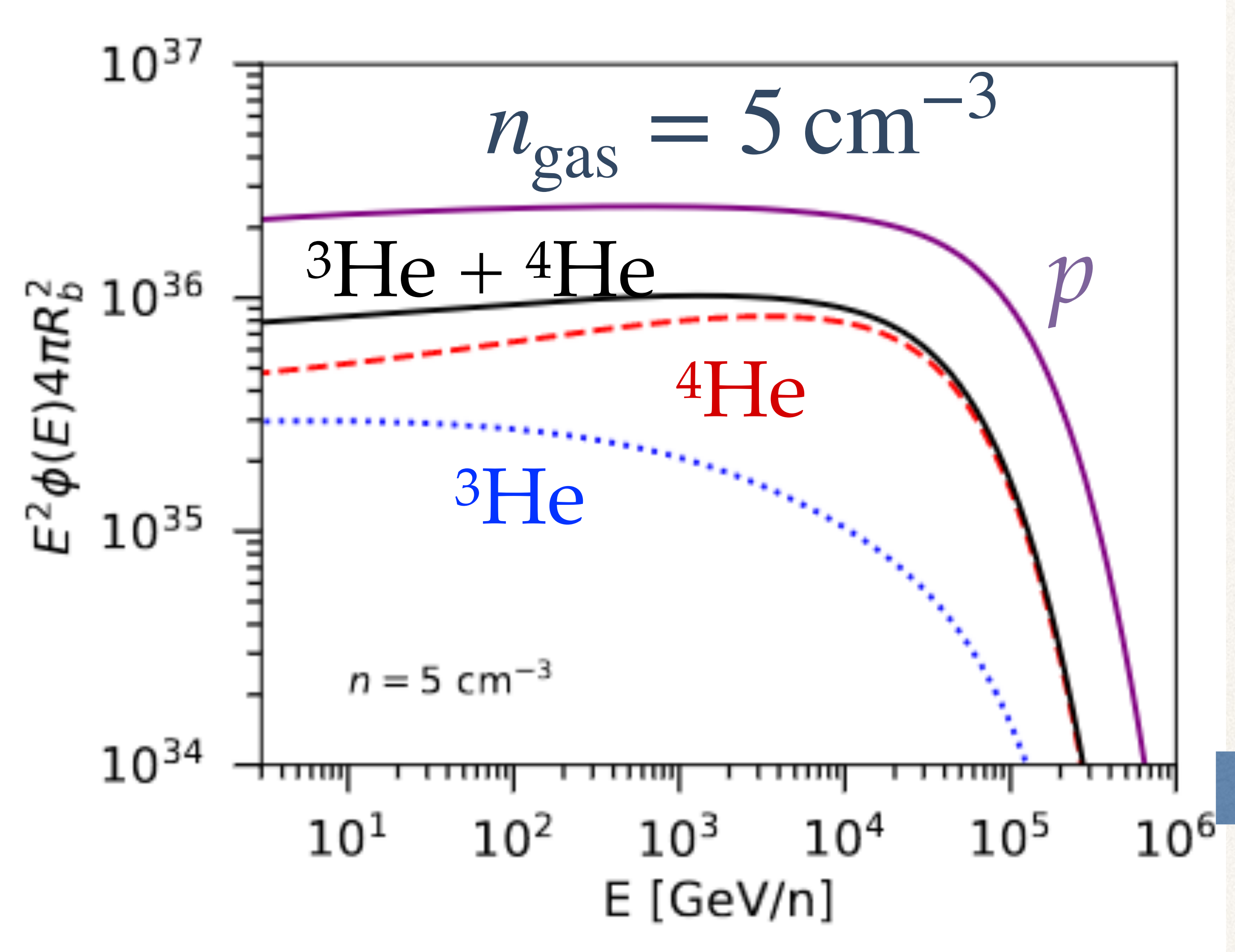


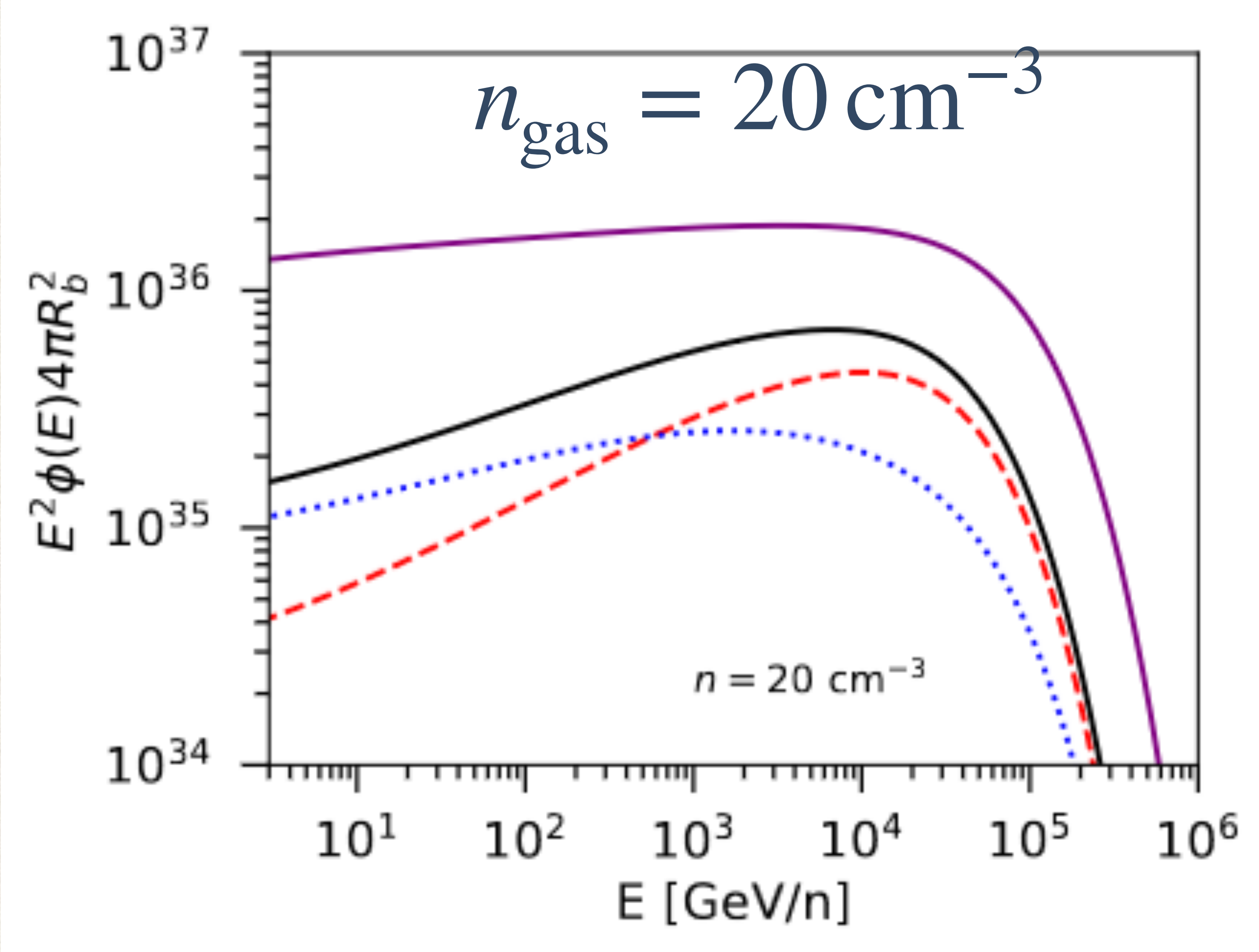
Temperature

L. Lancaster et al. (2021) -HD simulations

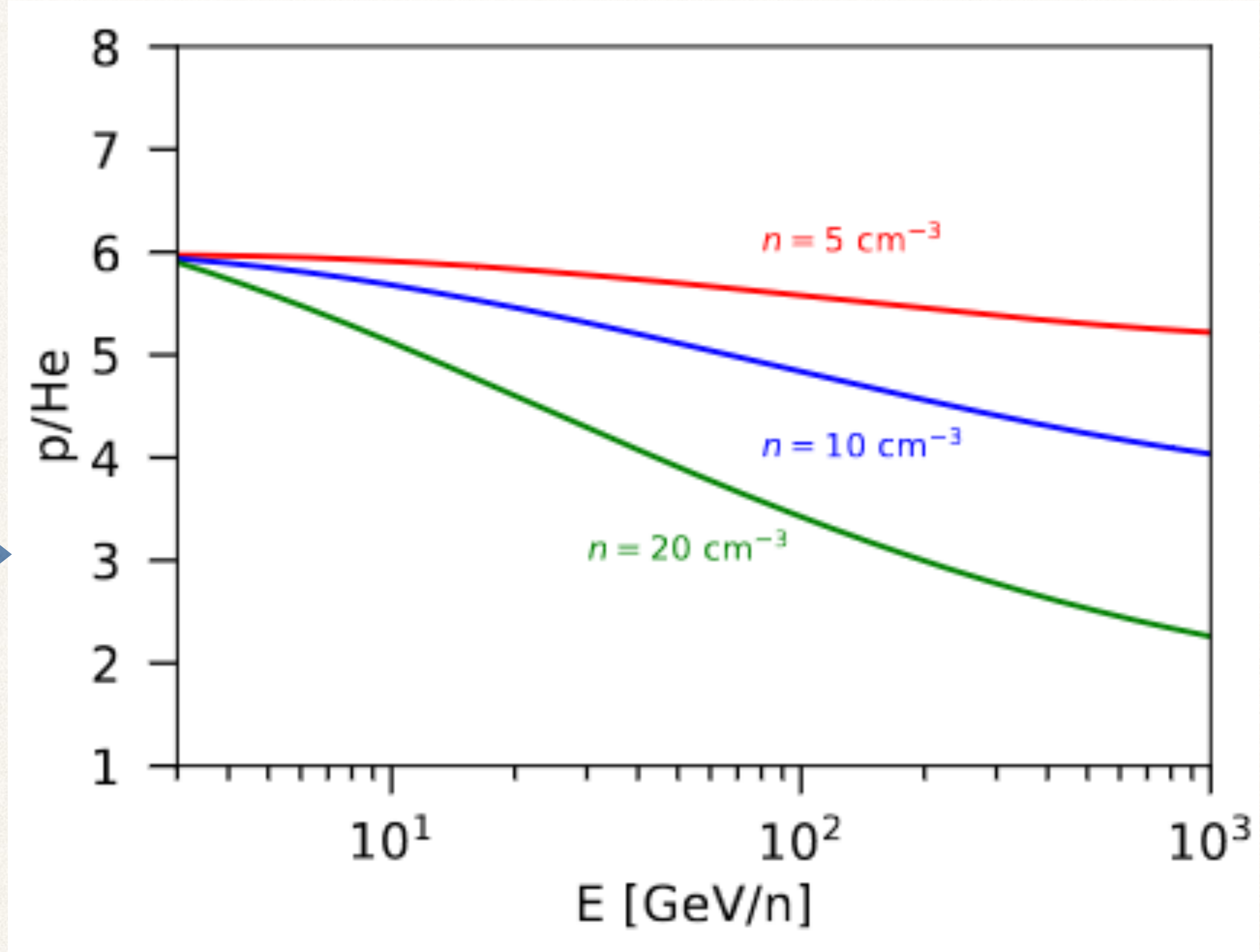
H and He spectra escaping from the bubble

[P. Blasi, GM (2024) arXiv:2307.11663]



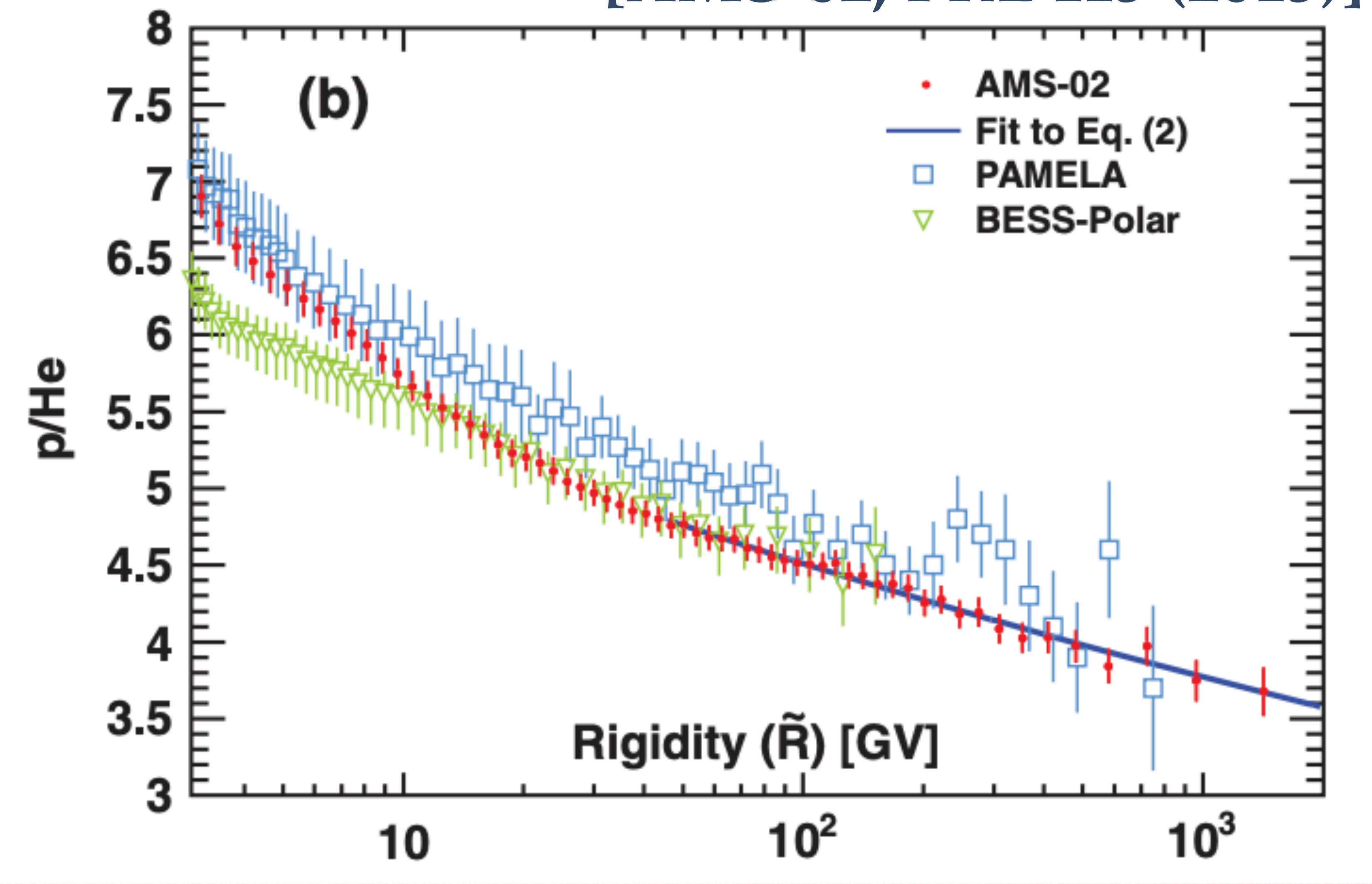


Ratio p/He at the source



Ratio p/He measured by AMS-02

[AMS-02, PRL 115 (2015)]



$L_{\rm wind} \simeq 10^{38}$ erg/s ; age $\simeq 3$ Myr

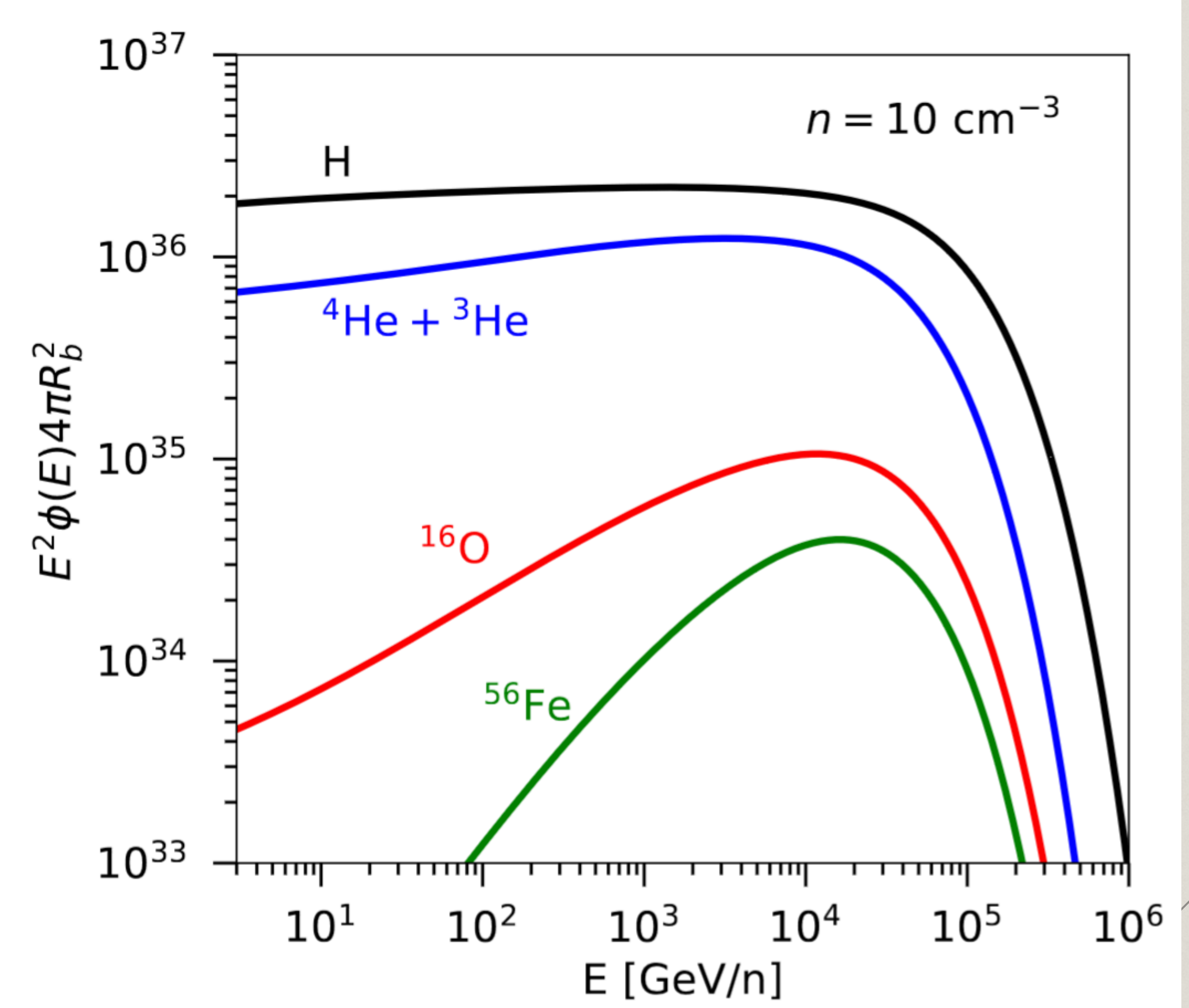
A fair comparison requires to account for the entire population of SCs with different luminosities

Heavier nuclei

[P. Blasi, GM (2024) arXiv:2307.11663]

Spectrum of different species escaping the bubble for a young MSC (like Cygnus OB2 $L_{\rm wind} \gtrsim 10^{38}$ erg/s)

- H and He can escape the bubble suffering only a little energy losses
- Spallation for heavier nuclei is much stronger ($\sigma_{\rm sp} \propto A^{0.7}$)
    - Nuclear have a harder spectrum
    - The flux normalisation is suppressed



Possible caveats:

- Heavier nuclei may be mainly produced by SNRs
- SNR acceleration may be modified in wind-bubbles
- Heavier nuclei may be mainly produced at later phase of the bubble, when the diffusion is not suppresses any more

SNR expanding into super-bubbles

Main effects on the SNR evolution

1. High temperature ⇒ low Mach number

Example: first SN expanding into the shocked wind

Shocked wind temperature: $k_B T_b = \frac{3}{16} m_p v_w$

Sound speed: $c_{\rm sound} = \sqrt{\gamma k_B T_b / m_p}$

$$\Rightarrow M = \frac{v_{sh}}{c_s} = 3.6 \left(\frac{v_{sh}}{5000\,\mathrm{km/s}}\right) \left(\frac{v_w}{2500\,\mathrm{km/s}}\right)^{-1}$$

CAVEAT:
Temperature may decrease due to radiative losses/heat conduction

$$\tau_{\rm cool} \simeq 6 \left(\frac{T}{10^6\,K}\right)^{1.7} \left(\frac{n}{0.01\,\mathrm{cm^{-3}}}\right)^{-1} \mathrm{Myr}$$

SNR expanding into super-bubbles

Main effects on the SNR evolution

1. High temperature ⇒ low Mach number
2. High turbulence ⇒ high magnetic field
   - low Alfvénic Mach number

Example: first SN expanding into the shocked wind

If the magnetic field is produced by wind turbulence:

$$\frac{B^2}{4\pi} v_w = \eta_B L_w \;\Rightarrow\; B_b \simeq 10,\mu\text{G}$$

Than the Alfvénic Mach number is

$$M_A = \frac{v_{\rm sh}}{v_{\rm A}} = \sqrt{\frac{4}{11\eta_B}\frac{v_{\rm sh}}{v_w}} \gtrsim 4$$

SNR expanding into super-bubbles

Main effects on the SNR evolution

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    - low Alfvénic Mach number
    - faster acceleration time

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The maximum energy increases:

$$E^p_{\max} \simeq 2\,\mathscr{F} \left(\frac{B_0}{10\mu G}\right) \left(\frac{M_{\rm ej}}{M_\odot}\right)^{-\frac{1}{6}} \left(\frac{E_{\rm SN}}{10^{51}\mathrm{erg}}\right)^{\frac{1}{2}} \left(\frac{n_0}{0.01\mathrm{cm}^{-3}}\right)^{-\frac{1}{3}} \mathrm{PeV}$$

↓

Diffusion needs to be Bohm-like

SNR expanding into super-bubbles

Main effects on the SNR evolution

1. High temperature ⇒ low Mach number
2. High turbulence ⇒ high magnetic field
    - low Alfvénic Mach number
    - faster acceleration time
    - enhanced syn. losses

Synchrotron loss time: $\tau_{\rm syn} = \frac{9 m_e^2}{4 r_0^2 c\, B^2} E^{-1}$

Advection time: $\tau_{\rm adv} = \frac{4 R_b}{3 v_w} \left(\frac{R_b}{R_s} \right)^2$

$$\tau_{adv} = \tau_{\rm syn} \;\Rightarrow\; E_{\rm esc} \lesssim 200 \left(\frac{B}{10\,\mu G} \right)^{-2} \text{GeV}$$

High energy electrons cannot escape from the bubble

Conclusions

- Stellar clusters play a crucial role in the origin of cosmic rays
  - They host the majority of core-collapse SNe
  - They shape the environment where SNRs expand
  - Powerful stellar winds may accelerate CRs in addition to SNR shocks
- CRs need to escape from the wind-blown bubble structure
  - Instabilities induce fragmentation of the dense bubble shell in small clumps
  - Average density felt by CRs in the bubble $\sim 10\,\mathrm{cm}^{-3}$ if diffusion in the clumps ~ diffusion in the bubble
    - ➡ The accumulated grammage produce harder spectra for heavier species
    - ➡ Good for p/He ratio, not for heavier elements
- It is crucial to better understand the time evolution of both wind bubbles and SNR inside them

BACKUP SLIDES

The Galactic propagation model

Ginzburg & Syrovatskii (1964)

Time-stationary transport equation in cylindrical geometry:

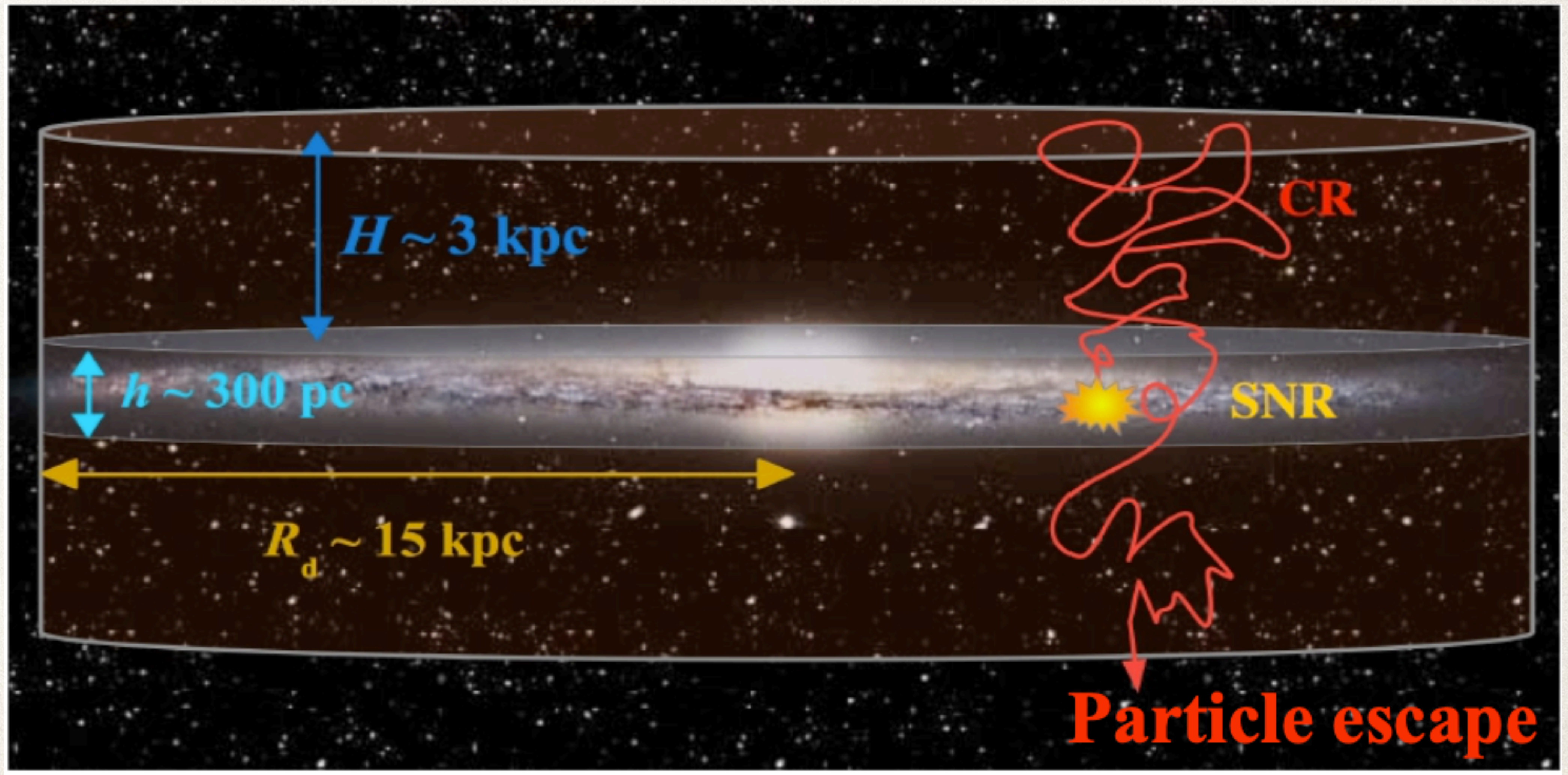
$$-\frac{\partial}{\partial z}\left[D(r,p)\frac{\partial f_\alpha}{\partial z}\right] + u(z)\frac{\partial f_\alpha}{\partial z} - \frac{du}{dz}\frac{p}{3}\frac{\partial f_\alpha}{\partial p} + \frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2\left(\frac{dp}{dt}\right)_{\alpha,\mathrm{ion}} f_\alpha\right] + \frac{\mu v \sigma_\alpha}{m}\delta(z) f_\alpha = Q(z,p) + \Sigma_{\alpha'>\alpha}\mu v \sigma_{\alpha'\to\alpha}\delta(z) f_{\alpha'}$$

Assumed free parameters

- Injection from SNR as power law: $Q_{\mathrm{inj}}(R) \propto R^{-\gamma_{\mathrm{inj}}}$
- The diffusion coefficient D(E) is assumed constant everywhere in the halo:

$$D(R) = \beta D_0 \frac{(R/\mathrm{GV})^\delta}{\left[1 + (R/R_b)^{\Delta s/s}\right]^s}$$

- CR advect along z direction: u_{adv}



Spectra of primary Cosmic Rays

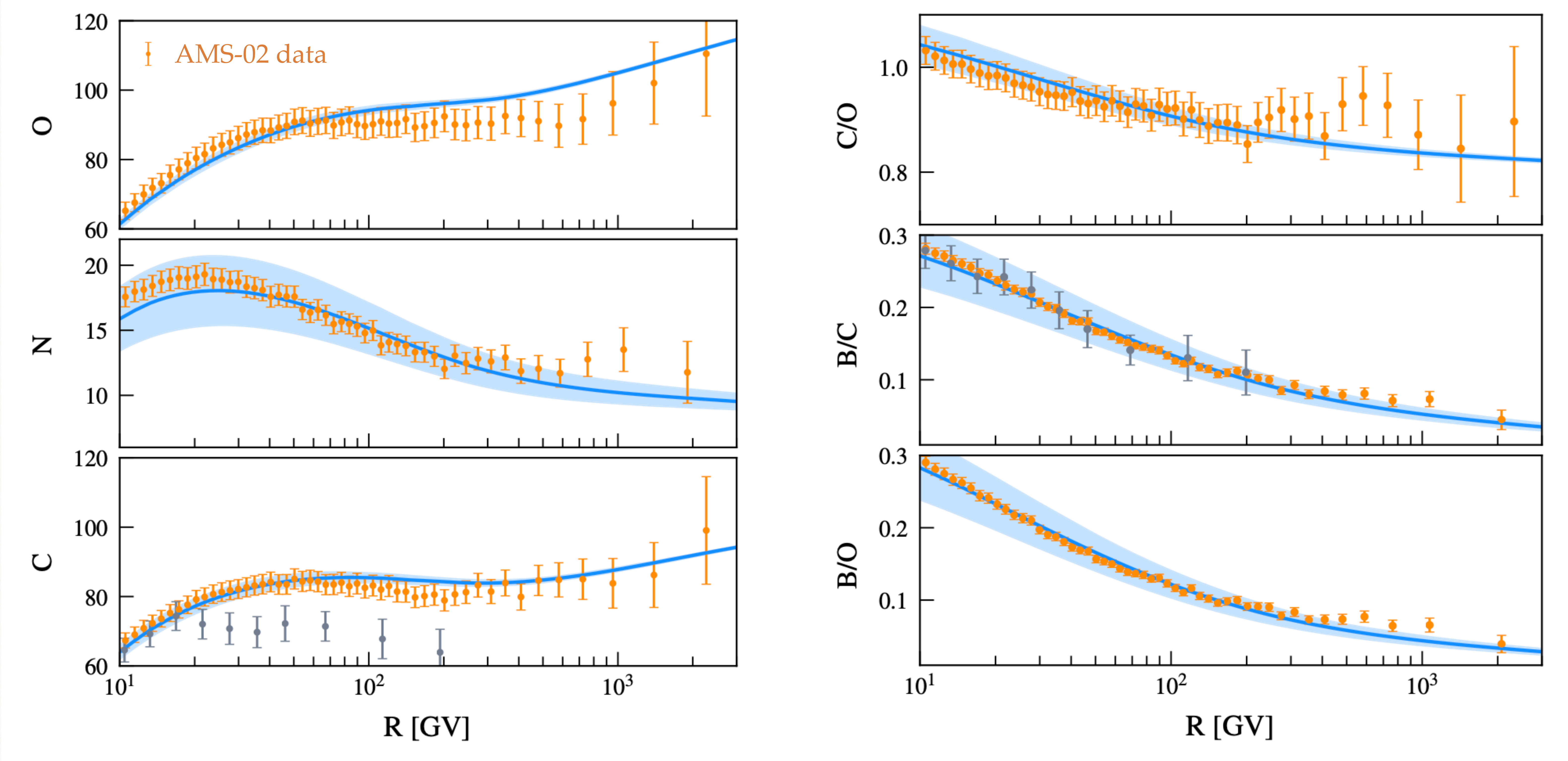
[Evoli, Aloisio, Blasi, PRL 2019]

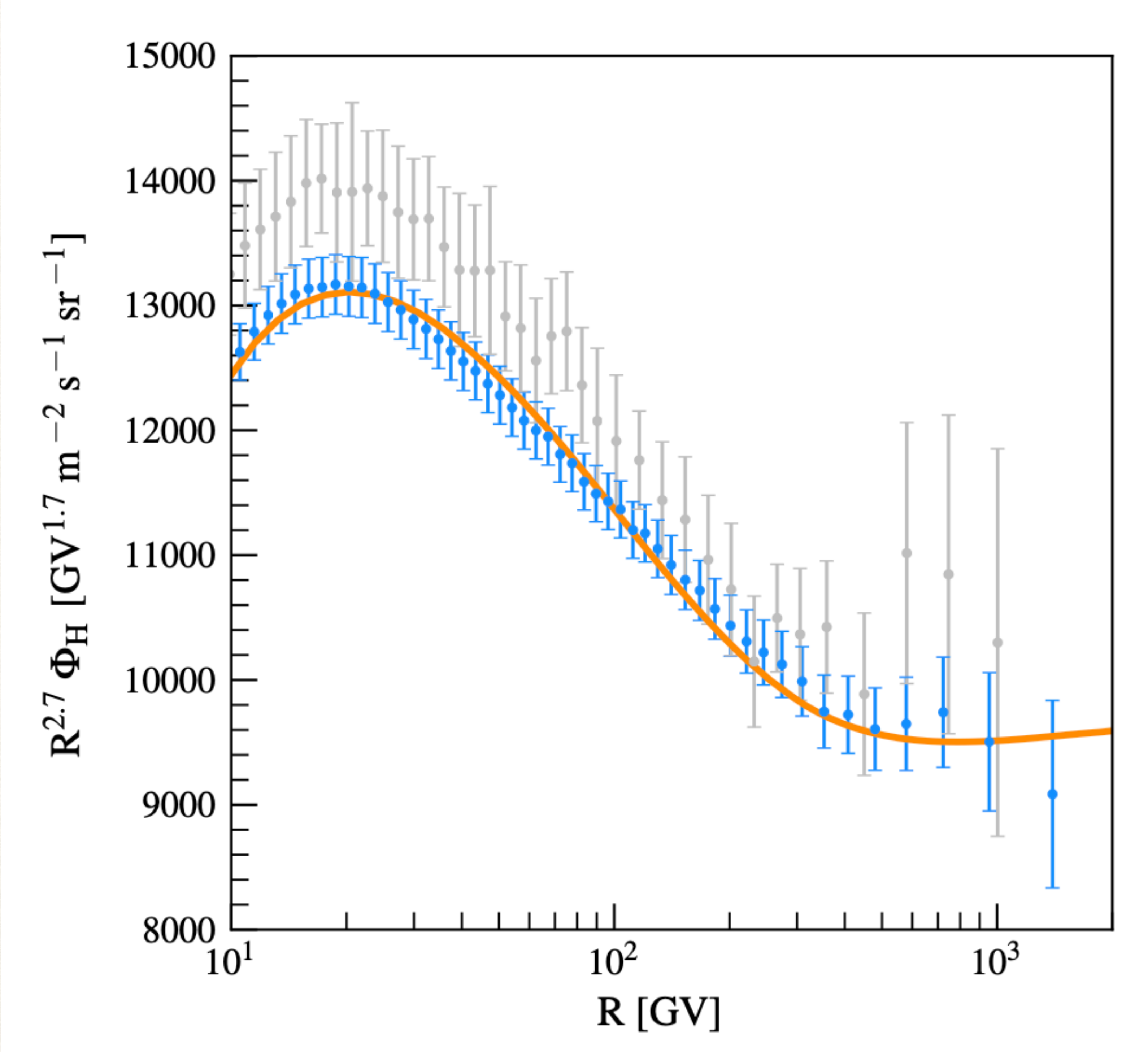
Assuming He with the same slope of CNO, the best fit gives:

$Q_{\rm inj} \propto p^{-\gamma}$ $\gamma_{\rm HeCNO} = 4.23$

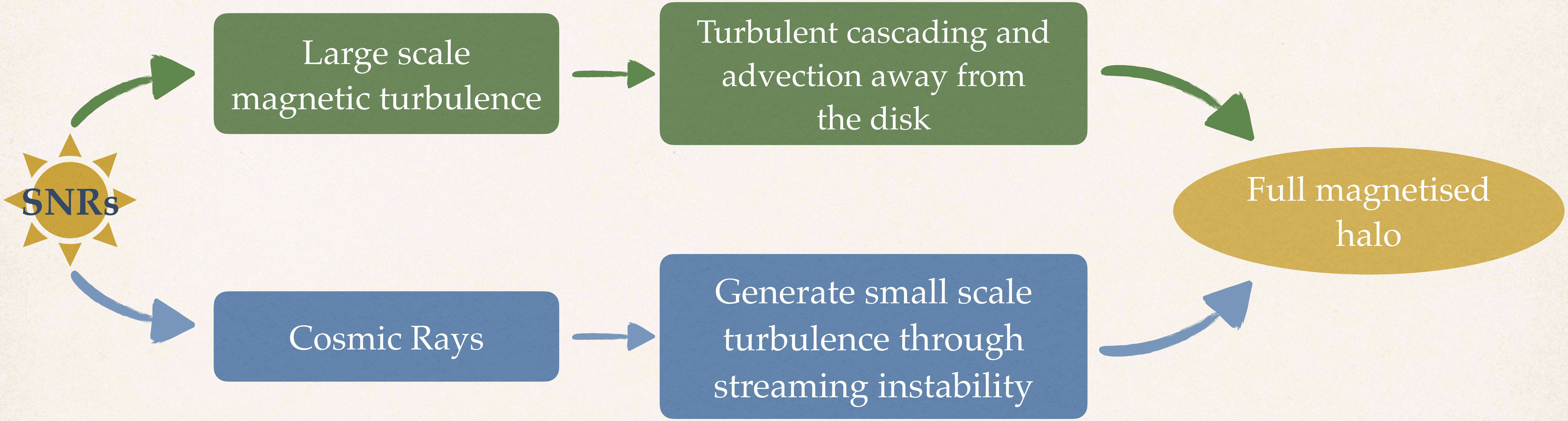
H requires steeper slope

$\gamma_{\rm H} = 4.31$





A self consistent magnetic halo model



SNRs

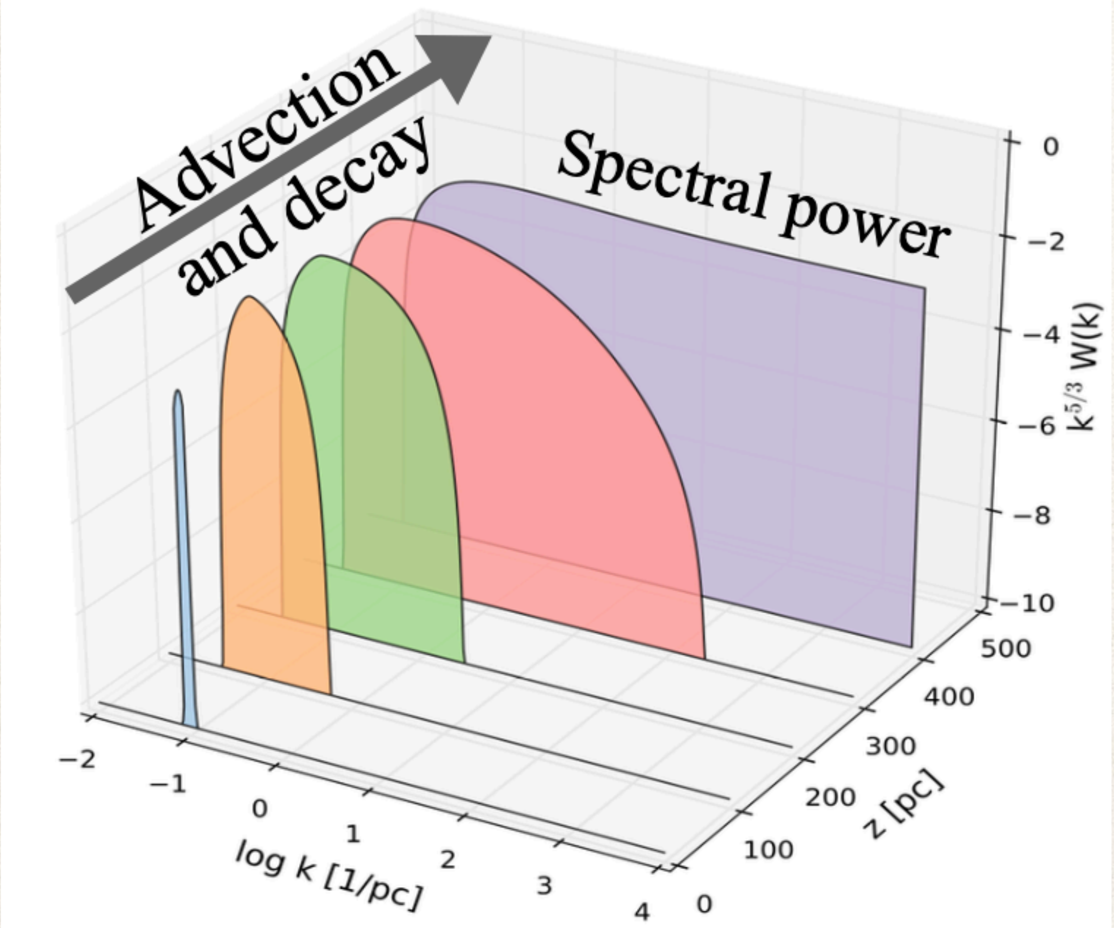
Large scale magnetic turbulence

Turbulent cascading and advection away from the disk

Cosmic Rays

Generate small scale turbulence through streaming instability

Full magnetised halo



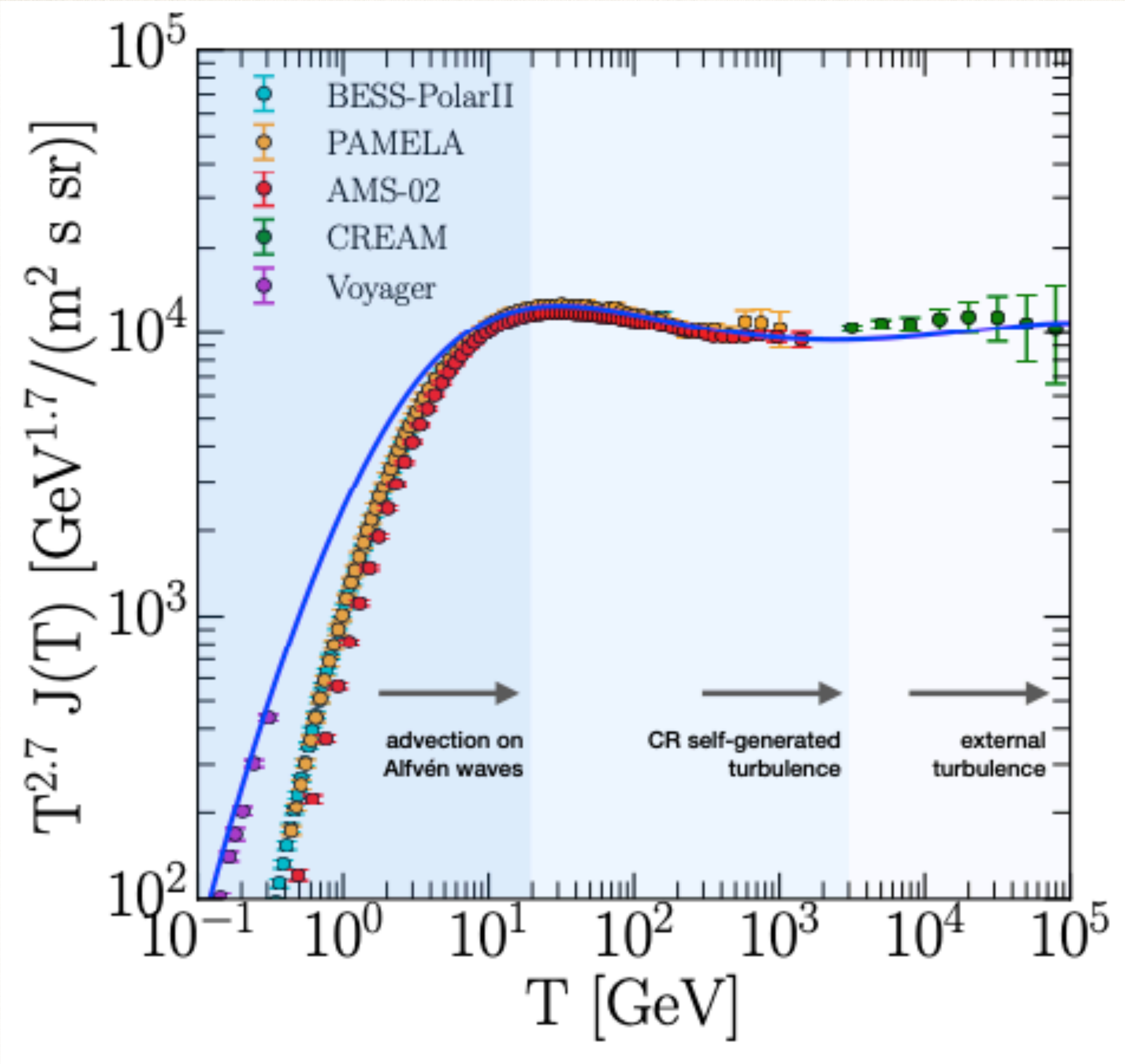
The size of the halo is determined by the competition of advection and cascading

$$\tau_{cascade} \approx D_{kk}/v_A^2$$

$$\tau_{adv} \approx H/v_A$$

$$\boxed{\tau_{cascade} \approx \tau_{adv} \Rightarrow H \approx \mathrm{kpc}}$$

Non-linear transport in the Galaxy



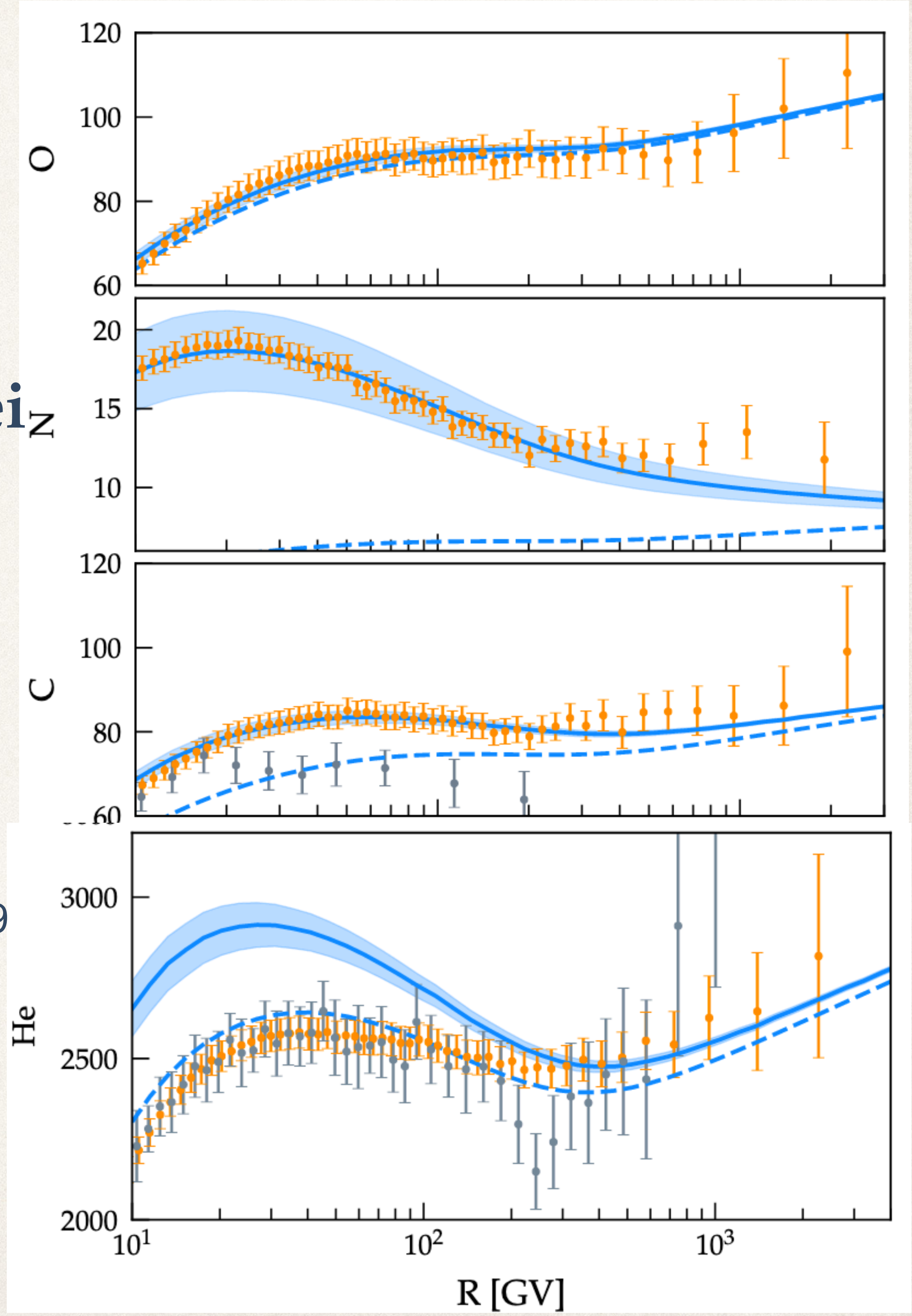
Protons

Evoli, Blasi, GM, Aloisio,
PRL (2018)

Primary nuclei
Ne, C, N, O

The same model
works well also
for other nuclei

Evoli, Aloisio, Blasi, PRD 2019



Unstable CR nuclei: Beryllium

Unstable secondary nuclei can be used to constrain the residence time of CRs inside the Galaxy, breaking the degeneracy between H and D.

- ^{10}Be is especially useful because of its long half-life of 1.39 My.

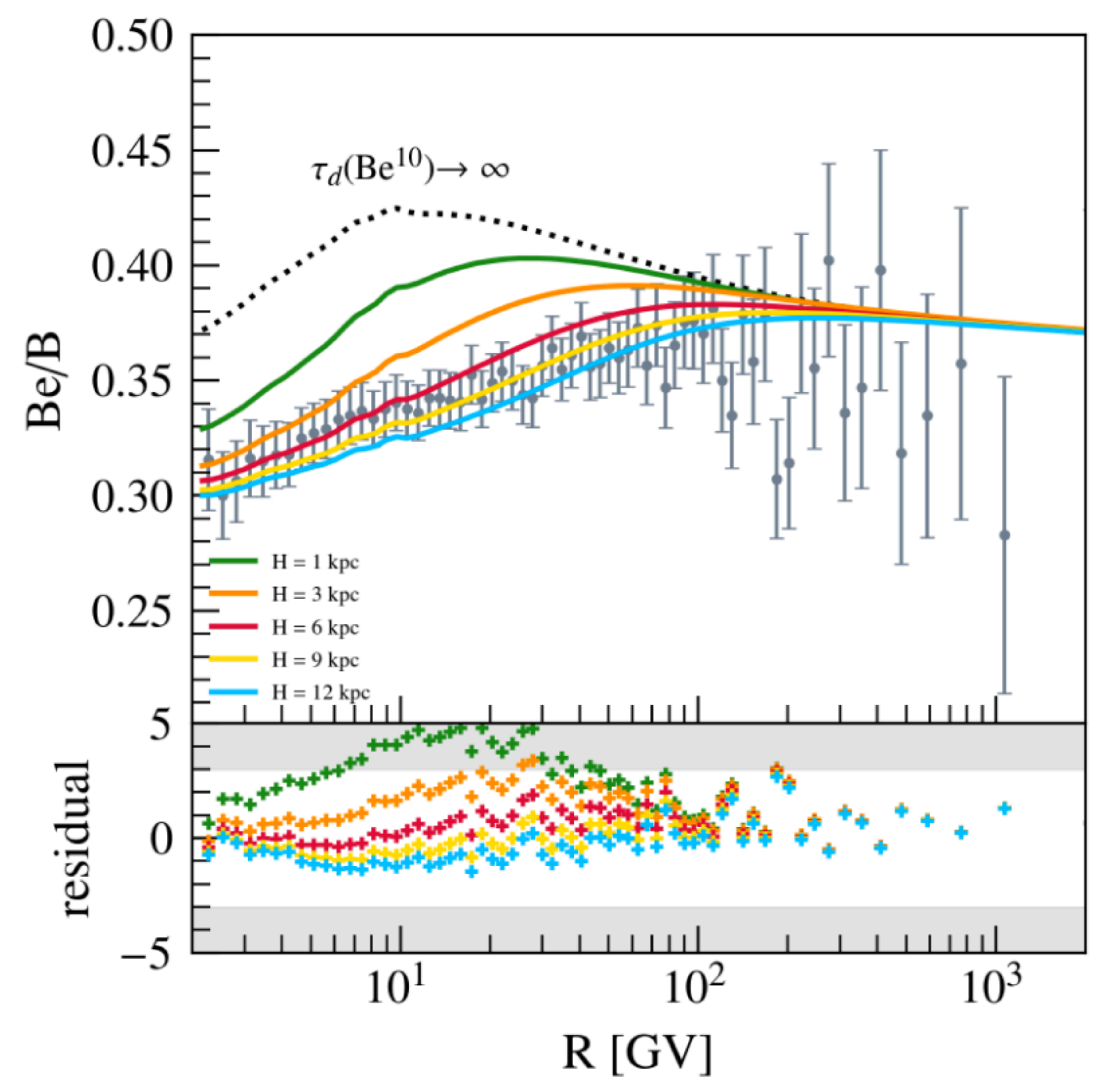
$$^{10}Be \rightarrow \, ^{10}B$$

- Decay reduces the flux of Be at small rigidities such that

$$\gamma \, \tau_{\rm decay} \lesssim \tau_{\rm esc}(R) = \frac{H^2}{2D(R)} \;\Rightarrow\; R \lesssim 100\,{\rm GV}$$

- AMS-02 measurements of **Be/B** are compatible with the standard picture of CR diffusion in a halo with thickness

$$\boxed{H \gtrsim 5 \text{ kpc}}$$



- A different analysis [Weinrich+ A&A 2020] of same data gives $H = 5^{+3}_{-2}$ kpc

- But conclusions are affected by uncertainties on the spallation cross section